2013

Investigation of Best Practices For Maintenance Of Concrete Bridge Railings

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INVESTIGATION OF BEST PRACTICES FOR MAINTENANCE OF CONCRETE BRIDGE RAILINGS

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Interdepartmental Program in Engineering Science

by
Angel Lence
B.S., Universidad Metropolitana, 2010
May 2014

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ABSTRACT

Biodeterioration on concrete surfaces of vertical elements of bridges represents a serious challenge to the highway infrastructure in Louisiana. This investigation aims to document the causes of biodeterioration of concrete surfaces and to document current conventional and state-of-the-art practices implemented to prevent and clean biofilm. A comprehensive literature review of previous research has been carried out in order to determine the cause and mechanisms of the biodeterioration as well as to identify current methods that state DOTs have implemented in order to maintain their bridges and allow them to function in optimal structural and performance conditions. A survey was developed and distributed among different states DOTs to determine current preventing and cleaning practices and their effectiveness. This review will serve as a baseline for future research projects on this topic as identified by the results of the synthesis. Results suggest that the main cause of biodeterioration of concrete surfaces is caused by micro-organisms' activity present at the surface. Furthermore, current practices used to prevent and clean biofilms growth are pressure washing, cleaning with biocides, and addition of photocatalytic nano titanium dioxide (TiO_2) in the concrete mix. From prevention and cleaning perspective, the use of photocatalytic nano TiO_2 in the concrete mix appears to be the most promising method in preventing microbial growth. However, further validation of this treatment is needed.

CHAPTER 1 – INTRODUCTION

The United States is a nation that has constantly been expanding its infrastructure and this trend does not seem to be slowing down any time in the future. This is especially true in the heavy highway industry, where more and bigger construction projects are being developed nationwide to interconnect cities and provide more and better options to drivers. This expansion goes hand and hand with infrastructure maintenance responsibilities that can be very challenging to accomplish. The state of Louisiana is no exception to this challenge; new highways, lanes, streets, and bridges are being built each year adding more maintenance needs to the Department of Transportation and Development (DOTD). Concrete is the most used construction material worldwide, with a production of over 10^{10} metric tons per year (Ashby 2012), and despite its reputation of being very strong and durable, it does require maintenance in order to perform and last as designed. The hot-humid climatic conditions present in the state of Louisiana (Department of Energy, 2010) triggers distresses in concrete such as biofilm development, which has a negative effect on both aesthetics and performance of the structure (Adamo & Violante 2000; Bastidas-Arteaga et al. 2008; Bott, 2011; de la Torre et al. 1992; Gaylarde et al. 2003). As shown in previous investigations, biofilms develop and grow easily when the right conditions are present, such as high relative humidity (60 to 100%) and temperature (70 to 95°F), which are very common in the state of Louisiana. As a consequence, visible stains and a relatively fast deterioration of bridges, roads, highways, and other structures are encountered in the state. This issue has triggered public complaints, which as a result have raised the need to find a practical and economic solution to be used by the Department. Figure 1 illustrates concrete surfaces with clear signs of biofilm growth (black stains) in Port Allen, Louisiana.

Figure 1
Development of Biofilms on Concrete Structures in Louisiana

The development of biofilms on concrete surfaces and structures is a sign of the initiation of the deterioration process of the structure. In order to slow down the negative effects of biofilms and extend the service life these concrete surfaces, maintenance methods such as pressure or power washing, soda, sand, and CO_2 (dry ice) blasting, cleaning with chemicals such has biocides; have all been employed. However, these methods vary in effectiveness, cost, safety, and time, and eventually biofilms continue to develop on the structure over time (Ray and Hanks 2012).

To address this problem, this study conducted a comprehensive literature review to identify the causes and types of biofilm deterioration and surveyed state agencies on currently used methods to prevent and eliminate biofilm development on concrete surfaces. It also identified other DOTs facing similar problems and the methods they use to prevent biofilm growth. In addition, the report also surveyed private companies that clean biofilm growth on concrete surfaces across the US to identify innovative solutions to this issue. A comparative analysis between widely used cleaning methods was conducted and presented in order to determine which method(s) should be evaluated for possible implementation in Louisiana.

1.1 Problem Statement

Literature shows that there are several methods to prevent and eliminate biofilm development in concrete structures. However, the selection of the method depends on many factors such as materials of the surface to be treated, climatic conditions of the region where the element to be treated is located, type of biofilms developing, severity of the biofilm problem, and others. The climatic conditions in Louisiana correspond mostly to the climatic region "Hot-Humid" according to the EPA. This type of climatic conditions promotes biofilm growth as a result of the warm temperatures and high levels of relative humidity. As a consequence, concrete surfaces present on bridges and highways are constantly presenting signs of biofilm growth. Therefore, there is a critical need to determine the most suitable method to prevent and eliminate biofilm growth for the prevailing climatic conditions in Louisiana.

1.2 Objectives

The primary objective of this study is to conduct a comprehensive literature review to determine causes of concrete biodeterioration and to present current practices employed or evaluated for cleaning and maintaining vertical concrete elements on bridges. The goal of this review is to identify possible preventive maintenance alternatives or construction materials that will enhance the resistance of these structures to biofilm growth and in turn reduce labor, costs, and traveling time delays. Based on this review, an economic analysis between the most common methods was conducted to determine which method is the most suited for the transportation industry in terms of safety, performance, durability, and cost.

1.3 Research Methodology

The activities conducted in this research were divided into four tasks as detailed below.

Task 1: Literature Review

A comprehensive literature review of previous research studies was conducted to investigate the following factors: the main types of microorganisms involved in the development of biofilms, the needs of the different microorganisms involved in biodeterioration, the process of deterioration of concrete elements caused by biofilms, and currents methods and solutions employed to control biodeterioration.

Task 2: Evaluation of Maintenance Procedures States' DOT Agencies

At the beginning of the research numerous maintenance manuals from several states' DOT agencies were collected and reviewed with the objective of collecting information on their current maintenance activities related to biodeterioration removal and control. Since none of the documents contained any information on maintenance procedures related to treating biofilms, with the exception of the New York State DOT, a survey was later created and distributed targeting DOTs and their maintenance office to retrieve additional information.

Task 3: Phone Interviews

Structured and non-structured phone interviews were conducted before and after the survey was carried, in order to gather specific information from experts and state practitioners in different fields related to biofilm issues.

The first set of phone interviews were carried before the survey was conducted, targeting in most cases private companies and experts in the biofilm removal industry. In most cases, these phone interviews aimed to gather specific information such as pricing, performance, safety, and durability on treatment methods such as sand blasting, dry-ice blasting, biocides, etc.

The second set of phone calls performed was carried after the survey was distributed in order to follow up, and expand information on certain states' survey responses.

Sample questions from phone interviews:

- Is mildew or mold (Biofilm) growth or staining of the concrete surfaces a concern for your agency?
- Is concrete bridge cleaning part of your state bridge maintenance program**?**
- Does your maintenance program include activities such as pressure or power washing, sand blasting, or cleaning with biocides?
- If monetary resources were available, would you treat biofilm development?

Task 4: Survey of Current DOT's Practices

A survey questionnaire was developed to investigate current maintenance practices performed by highway agencies across the U.S. The objective of this questionnaire was to determine which states are facing biofilm issues, whether or not scheduled or non-scheduled maintenance procedures are being employed, and if so, what methods are being employed. Furthermore, the survey also targeted private companies with experience on biofilms issues, not only in the heavy highway industry but also in the housing and industrial industries.

Task 5: Cost Analysis

An economic analysis between the most common methods was conducted to determine which method is the most suited for the transportation industry in terms of safety, performance, durability, and cost.

1.4 Overview of Thesis Organization

The second chapter is an overview that aimed at identifying the main microorganisms responsible for concrete biodeterioration, which environmental conditions and nutrients are required by these microorganisms in order to exist and deteriorate concrete, what are the mechanisms employed by microorganisms to deteriorate concrete, and which are the methods utilized in different industries to treat this problem

The third chapter is a summary that reviews the biofilm treatment methods employed in different industries and discusses their application to the highway industry. Furthermore, chapter 3 contains the survey and the survey results, and the cost analysis comparing all the methods currently employed or evaluated for application on treating biofilms.

Chapter four contains the summary and conclusions of this investigation. In that chapter a comparison of all treatment methods is conducted and a final method is recommended on top of all.

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CHAPTER 2 - OVERVIEW OF MICROORGANISMS RESPONSIBLE FOR CONCRETE BIODETERIORATION, BIODETERIORATION MECHANISMS, AND BIODETERIORATION TREATMENT METHODS

2.1 Causes and Mechanisms of Concrete Biofouling

The most important cause of concrete biofouling (i.e., stains, discoloration, etc.) is the growth of microorganisms at the surface. Microorganisms are living beings that are too small to be seen with the naked eye; they can be detected with a microscope. It is important to have a basic understanding of how microorganisms grow on concrete surfaces as well as which micro-organisms cause concrete deterioration. The most common types of microorganisms involved in bio-fouling of concrete are bacteria, fungi, algae, and lichens (Gaylarde et al. 2003; Sand 1997).

2.1.1 Bacteria

Bacteria are very small organisms with sizes usually smaller than one micron (1μm) (Sanchez-Silva and Rosowsky 2008). These are unicellular (one cell) organisms whose genetic materials are not contained in a nuclear membrane as shown in Figure 2. They are also known as “prokaryotes”. Bacteria can create formations like chains, pairs, clusters, and other groupings. The reproduction of bacteria is a simple process of division called binary fission, where a bacterium subdivides into two equal daughter cells (Tortora et al 2004).

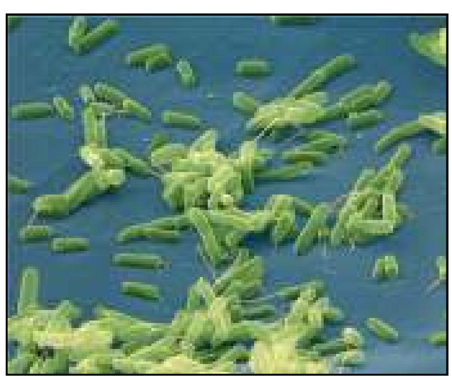

Figure 2
Microscopic Image of Bacteria (Mckinney 2009)

When bacteria grow on surfaces, they do not cause any visible stains like other microorganisms; therefore, they do not affect the aesthetics of construction materials (Escadeillas et al 2007). However, some bacteria types have been shown to deteriorate concrete as shown in Figure 3, such as Thiobacillus concretivorus, later renamed as Thiobacillus thiooxidans (Parker 1945; Gu et al 1998), and others have been related to health problems. Bacteria can be found everywhere; they can live and reproduce in water, air, soil, skin, and even food (Ray and Hanks 2012).

Figure 3
Acid Producing Bacteria Penetrating and Colonizing Concrete (Linabond Eurasia Limited)

The main types of bacteria responsible for causing damage on concrete surfaces include cyanobacteria, nitro-bacteria, sulfur-reducing bacteria, and sulfur-oxidizing bacteria (Sanchez-Silva and Rosowsky 2008). Table 1 shows the deteriorating effects that some types of bacteria have on concrete. The types of bacteria listed in Table 1 are classified as either autotrophic or heterotrophic, and aerobic or anaerobic bacteria based on their lifestyles. However, they all have different needs for pH and temperature. Cyanobacteria are the only type of bacteria that have a wide range of temperatures and pH requirements; this means that it can survive under different environmental conditions. The other types of bacteria show a more limited range for temperature and pH requirements. This information can be useful in order to identify what kind of bacteria might be present in different locations and to diagnose causes of concrete bio-fouling. The deterioration that these microorganisms exert on concrete range from increase in crack sizes, solubilization of cement components, concrete corrosion, and chemical changes (Bastidas-Arteaga et al 2008; Sand 1997; Giannantonio et al. 2009).

Table 1
Principal effects of bacteria on RC structures (Gaylarde et al. 2003)

Bacteria Type	**Lifestyle**	**Temperature and pH ranges**	**Damage on concrete**
Cyanobacteria	Autotrophic, aerobic or anaerobic	- 60 to 85 °C - Wide range of pH	Generate tensile stresses leading to an increment in the size of cracks
Nitrobacteria	Heterotrophic and anaerobic	- 18 – 25 °C - pH < 7.5	Nitrifying bacteria produce calcium nitrate by solubilizing some cement components
Sulfur-reducing bacteria	Heterotrophic and anaerobic	- 25 – 44 °C - 5.5 < pH < 9	Produce H_2S that is used for the sulfur-oxidizing bacteria to produce sulfuric acid. (concrete corrosion)
Sulfur-oxidizing bacteria	Heterotrophic and anaerobic	- 25 – 44 °C - 2 < pH < 9	Produce sulfuric acid, acetic acid, sulfates, sulfur, sulfites and polythionates that affect concrete chemically

2.1.2 Fungi

The fungi category includes molds, mildew, yeasts, and mushrooms. These organisms may be multicellular or unicellular, depending on the specie. The most common specie of fungi is molds. Molds usually create visible biofilms called *mycelia*, which are composed of *hyphae* (large filaments) (Tortora et al. 2004). Fungi do not ingest nutrients, instead, they absorb them. All fungi are chemoheterotrophs, which mean that they require organic compounds as nutrients (Tortora et al. 2004).

Fungi are different from plants; while plants get their nutrients through photosynthesis, fungi absorb nutrients from the substrate on which they grow, by secreting enzymes that breakdown cellulose material around them. Just as bacteria, fungi can be found under a wide range of climatic conditions. However, fungi accounts for a larger fraction of the biomass of the planet than humans (Ray and Hanks 2012). That is why humans always come in contact with different species of fungi. Out of approximately 100,000 species of fungi that have been identified, only several hundred can produce mycotoxins, which are toxic compounds thought to be produced by the organism to defend itself (Ray and Hanks 2012). Figure 4 shows concrete damage caused by fungi.

Figure 4
Concrete Damage Caused by Fungi (Giannantonio et al. 2009)

Fungi consist of two main components as shown in Figure 5, the *Hyphae* and the *Spores. Hyphae* are large vegetative filaments that are part of fungi. As a fungus grows, more *hyphae* will be created. Large mass of *hyphae* is also known as mycelia. *Spores* are the reproduction mechanisms of fungi. *Spores* are very small, ranging from 2 to 20 µm (microns). When a fungus matures, it will produce spores and send them airborne or waterborne to create new colonies. Because of their small sizes, spores are respirable, and some fungi species create spores that may be allergenic to some humans. Spores can travel in water or air and land in surfaces, and when provided with the right conditions such as humidity and nutrients, they can form new colonies (Ray and Hanks 2012). Generally, fungi can be found in places where temperatures range from 25 to 30°C (Bastidas-Arteaga et al. 2008).

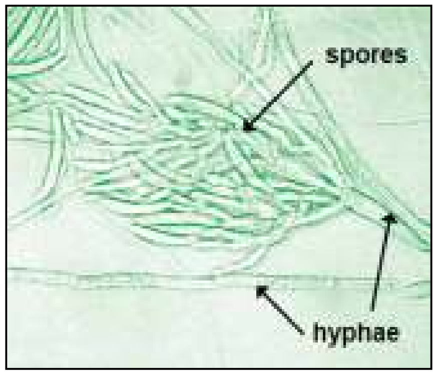

Figure 5
Fungi parts (Iowa Soybean Association 2010)

Fungi can affect concrete by two means; mechanical and chemical. Mechanical deterioration of concrete is produced by the penetration of the *hyphae* (a component of fungi) into the concrete microstructure. The chemical deterioration occurs because some species of fungi produce organic and inorganic acids that can precipitate salts (Bastidas-Arteaga et al. 2008). Table 2 presents information on common molds and their characteristics. This table shows the water activity requirements for some of these species, which can be used in order to prevent its growth by reducing surface's humidity. Water activity represents the intensity with which water associates with other materials, it is defined as the vapor pressure of a liquid divided by that of the pure water at the same temperature. The higher the water activity of a substance or material is, the higher the tendency of that material to support microorganisms.

Table 2
Common molds and characteristics (Ray and Hanks 2012)

Fungi	Toxicity	Water IIF	Aw (%)	Characteristics
Ascospores	▲	●		Found everywhere
Aspergillus	▲	●	70-82	Outside on plant debris. Indoors on a variety of substrates
Fusarium	▲	●	86-91	Outdoors on soil and plants. Indoor in humidifiers and on wet cellulose building materials.
Pithomyces				Not common indoors, but may grow on paper
Stachybotrys	▲	●	94	Outdoors on decaying plant matter. Indoors on water damage building materials, cellulose material like ceiling tiles, drywall, insulation backing, paper, textiles.
Tricoderma	▲		90	Indoors on textiles, wet cellulose materials and paper. It can produce T-2 toxin. It has been associated with immune-comprised individual.

Legend

▲ = Water intrusion indicator fungus capable of producing mycotoxins

● = Water intrusion indicator fungus

IIF = Intrusion indicator fungus

AW = Water Activity

2.1.2.1 Life Cycle of Fungi

The life-cycle of fungal microorganisms shown in Figure 6 starts when a spore lands on a substrate that can provide enough nutrients and humidity. After the spore lands on a supportive substrate, it will start growing filamentous structures called hyphae, spreading them in a circular shape. When the mycelia has been formed, fungi will start creating sporangia, which is the structure that holds the spores, and finally, the spores are released to the air or water and create new colonies in another supportive substrate.

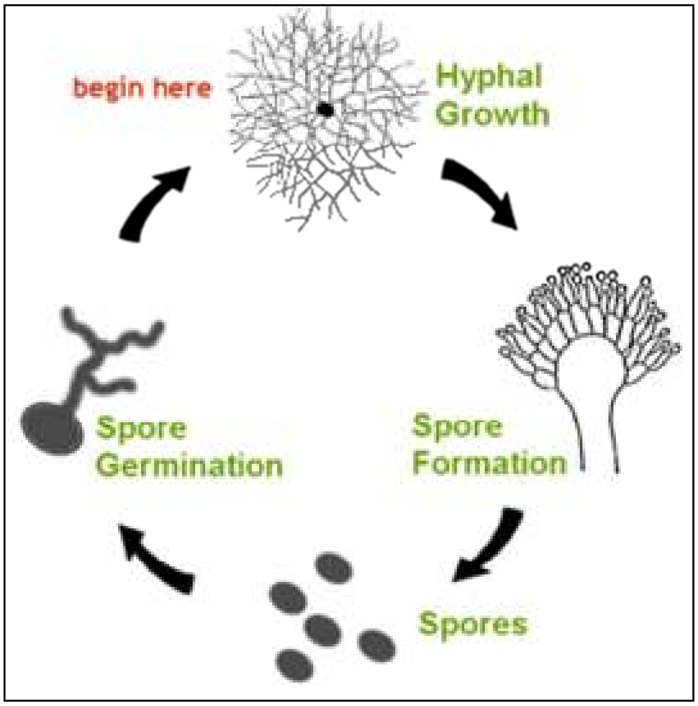

Figure 6
Life-Cycle of Fungi (Power Vac America)

2.1.2.2 Microbial volatile organic compounds (MVOCs) and Health Effects

Fungi can generate gases as product of the reaction of the enzymes produced by fungi to dissolve nutrients. These gases are known as Microbial Volatile Organic Compounds (MVOCs). MVOCs have been related to irritation and problems experienced by susceptible individuals, but are not a serious risk generally. The MVOCs correspond to the musty smell that these microorganisms generate, typical in indoor spaces supporting mold growth. MVOCs may cause irritant reactions to humans. Usually, these reactions cease when the person is removed from the environment that contain the MVOCs. The typical reactions are: headaches, burning eyes, rashes, and rhinitis. In addition, fungi cause some infectious diseases including athlete's foot, ringworm, and yeasts infections (Ray and Hanks 2012).

2.1.3 Algae (singular: Alga)

Algae organisms can reproduce sexually and asexually. They come in a large variety of shapes. Their cell walls contain cellulose, similar to plants. Because of their photosynthesis process, they do not require organic compounds; they just need air, sunlight, and a relatively high amount of water or humidity (when compared to other microorganisms) (Tortora et al. 2004). A microscopic image of algae is shown in Figure 7. Algae can affect concrete by absorbing minerals from concrete such as calcium, magnesium, and silica (Bastidas-Arteaga et al. 2008). Figure 8 shows example of concrete stained by algae and how it was restored by cleaning.

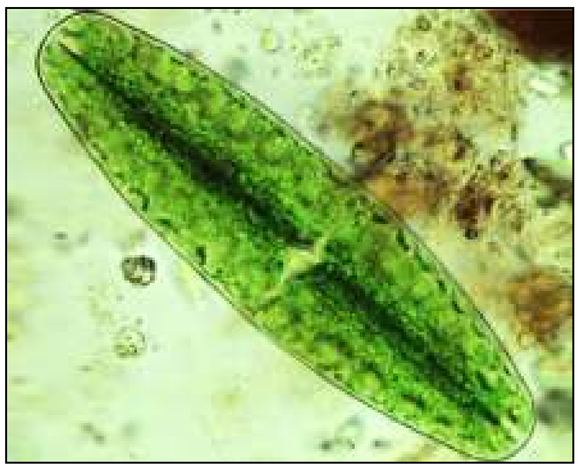

Figure 7
Microscopic image of algae (Inhabitat 2012)

Figure 8
Concrete colonized by algal species (green algae); Before and After cleaning (Eco-Wares)

2.1.4 Lichens

Lichen is a combination of fungi and green algae. These two organisms support each other symbiotically to survive. Fungus provides water to algae and algae take from the fungus inorganic substances. This characteristic of the lichens allows it to survive in very hostile habitats. Lichens are usually the first organisms to colonize newly exposed surfaces (Tortora et al. 2004). These organisms excrete organic acids that can deteriorate (weather) the substratum on which they grow (chemical bio-deterioration), and also can physically deteriorate it by disaggregating the minerals by expanding and contracting its mycelium (Adamo and Violante 2000; Wilson and Jones 1983). Figure 9 shows damage induced on a granite surface by Lichens.

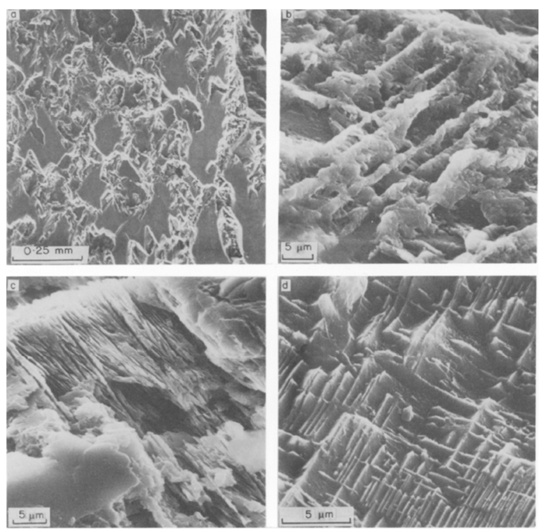

Figure 9
Surface damage caused by crustose lichens. Images show etched out minerals from granite (SEM images) (Wilsom and Jones 1983)

2.2 Factors Affecting Biofilm Growth

Microorganisms responsible for biodeterioration, are capable of colonizing and growing on concrete in aggressive environments, when certain favorable conditions are present such as availability of water and low levels of pH (Bastidas-Arteaga et al. 2008; Sanchez-Silva and Rosowsky 2008). These conditions include (Bastidas-Arteaga et al. 2008):

- Relative humidity between 60 and 98%
- Long cycles of humidification and drying, or freezing and defrosting
- High CO_2 concentrations
- High concentrations of chloride ions or other salts (marine-like environments)
- Elevated concentrations of sulfates and small amounts of acids (sewer pipes or residual water treatment plants.

2.2.1 Nutrient Needs of Microorganisms

Microorganisms need nutrients in order to survive on any surface. Autotrophic (photosynthetic) microorganisms such as cyanobacteria and algae absorb carbon from CO_2 emissions in the atmosphere and use sunlight as an energy source. Heterotrophic organisms need organic material as a direct nutrient (Gaylarde et al. 2003). Tables 3 and 4, presents the nutrient needs for different types of microorganisms, based on their nutritional category (Kumar and Kumar 1999).

Table 3
Classification of microorganisms based on their nutritional requirements (Kumar and Kumar 1999)

Nutritional Category	**Energy Source**	**Carbon source**	**Groups of Organisms**
Photoautotrophs or Photolithotrophs	Sunlight (photosynthetic organisms)	CO_2	**Aerobic Organisms:** -Cyanobacteria -Algae (Bacillariophyta or diatoms) -Algae (Chlorophyta) -Lichens -Mosses and liverworts -Higher plants
Chemoautotrophs or chemolithotrophs	Redox reactions (photosynthetic organisms)	CO_2	**Aerobic organisms:** -Hydrogen bacteria -Iron bacteria -Nitrifying bacteria

Table 4
Classification of microorganisms based on their nutritional requirements (Kumar and Kumar 1999)

Nutritional Category	Energy Source	Carbon source	Groups of Organisms
Photoheterotrophs or photoorganotrophs	Sunlight (photosynthetic organisms)	Organics	**Aerobic Organisms:** -Photosynthetic bacteria -Some algae
			Anaerobic organisms: -Green and purple sulfur bacteria -Purple non-sulfur bacteria
Chemoheterotrophs or chemoorganotrophs	Redox reaction (chemosyntetic organisms)	Organics	**Aerobic Organisms:** -Actinomycetes -Animals -Fungi -Respiratory bacteria
			Anaerobic organisms: -Fermentable bacteria -Denitrifying bacteria -Sulfur-reducing bacteria

2.3 Mechanism and Effect of Biofilm Growth on Construction Materials

In order to identify methods to control and prevent the colonization and formation of biofilms on concrete surfaces, it is important to identify the main types of microorganisms responsible for the production of the visible stains, explain how they colonize concrete surfaces, and the mechanisms of these microorganisms for deteriorating concrete surfaces. Construction materials including concrete have a characteristic called bioreceptivity (Gaylarde et al. 2003; Guillitte and Dreesen 1995), which is the capability of such material to host or allow living species to colonize it. When biofilms develop in concrete surfaces, they are able to deteriorate the surface by two mechanisms (Gaylarde et al. 2003):

- By absorbing components present in the substrate (concrete) and using them as nutrients, and/or,
- Producing organic and inorganic acids that attack concrete's components solubilizing them.

Gaylarde et al. divided biodeterioration of concrete material into three types:

- Physical or mechanical biodeterioration;
- Fouling or soiling (aesthetic); and
- Chemical.

The first type of biodeterioration (physical or mechanical) takes places when microorganisms change the physical structure of the material by growing or moving, but not by using the substratum as a nutrient source. The second type (fouling and soiling) occurs when a layer of microbes (biofilm) develops in the material surface. This biofilm is created by microorganisms: dead microorganisms, excreted products, and/or metabolic products. Fouling and soiling of a material surface will cause a visible stain on the surface, which usually affects the aesthetic aspect of the material but not its performance. The last type of biodeterioration (chemical) occurs due to two factors: 1) excreted product of microorganisms as organic or inorganic acids, affect the material's microstructure and components, and 2) microorganisms use the surface (substratum) as a nutrient source.

When a construction material such as concrete becomes colonized by microorganisms, the humidity and microstructure of the material surface changes. Consequently, the roughness of the surface increases, rendering the surface more capable for growth and attachment of microorganisms. Minerals contained in Portland cement and aggregates can be used by microorganisms directly as nutrients and in other cases they can be solubilized by microbial metabolites (Gaylarde et al. 2003).The solubilization of minerals in the concrete mix is caused by metabolic reactions of microorganisms present in the surface. Nitrifying bacteria and *Nitrosomas* produce nitric acids in their metabolic processes, nitric acids then solubilize calcium present in cement and form soluble calcium nitrate (Gaylarde et al. 2003). When this process (solubilization of minerals) occurs, the microstructure of the surface becomes unstable and the deterioration process starts.

A similar explanation can be found in Sanchez-Silva and Rosowsky, which states that reinforced concrete structures' integrity can be affected by microorganism activity. Sanchez-Silva and Rosowsky described a three-step process by which microorganisms can compromise the integrity of a concrete structure (Sanchez-Silva and Rosowsky 2008):

- Colonization and initial deterioration of concrete surface;
- Penetration of microorganisms into the concrete matrix; and
- Initiation and propagation of cracks within the concrete.

Immediately after construction, concrete generally shows high levels of alkalinity, with pH levels between 11 and 13. When concrete show these high levels of pH, it is almost immune to colonization by microorganisms because only a few species can develop in such high levels of pH, these species are called *Alkalinophilic* (Madigan et al. 2004) Given time, the interaction between concrete and CO_2 in the environment gradually decreases its pH levels, eventually reaching levels that allow bacteria to colonize and grow on concrete (pH 9-9.5) (Sanchez-Silva and Rosowsky 2008). After reaching these levels of pH, different species of bacteria and microorganisms start to form a biofilm on the concrete surface. This biofilm starts a deterioration process where different organic and inorganic acids, which are excreted by microorganisms, react with concrete solubilizing cement components. The microscopic sizes of microbes allow them to penetrate deep within the concrete matrix by filtering through the micro cracks and capillarity of concrete. The penetration of microorganisms into the concrete matrix, results in an increased concrete porosity, which then changes the concrete's coefficient of diffusion and internal conductivity. Therefore, corrosion of the steel reinforcement becomes easier for oxidizing and corroding agents present in the environment.

Once the reinforced steel is exposed to the environment, it becomes susceptible to the effects of corroding agents. The corrosion process of the reinforcing steel starts when the concentration of chloride on the steel surface surpasses a certain established value (Sanchez-Silva and Rosowsky 2008). The corrosion process generates corrosion products that start to fill the voids and open spaces between the steel and concrete. Finally, when these spaces are filled with corrosion products, the stress produced by their expansion increase until it exceeds the tensile strength of concrete and creates cracks (Sanchez-Silva and Rosowsky 2008; Stewart and Val 2003).

Table 5 shows the effects of different microorganism's activity on construction materials. Depending on the activity that the microorganism performs (physical presence, acid production, etc.), different kinds of effects will be produced on the surface of the material acting as a substrate (wood, polymers, concrete, stone, paint, etc.). The consequences can range from discoloration and retention of water to degradation of material, corrosion and weakening and dissolution of the material acting as the substrate.

The common effects that these microorganisms have on concrete surfaces range from: leaching of the minerals from the concrete matrix, visible stains created by biofilm layers, and acid production that decomposes minerals present in concrete's surface.

Table 5
Effects of microorganisms on building materials (Gaylarde et al. 2003)

Microorganisms	Activity	Effect(s)	Material
Algae, photosynthetic bacteria	Physical presence	Increased growth of heterotrophic organisms	Any clean surface
Fungi, bacteria; Filamentous fungi	Hydrolytic enzymes	Breakdown of components; Degradation of short-chain additives	Wood, painted surfaces, polymers, mortar, concrete
Fungi, actinomycetes, cyanobacteria, algae	Filamentous growth	Disaggregation of material	Stone, concrete, mortar, wood
Fungi, bacteria	Acid production	Corrosion	Stone, concrete, mortar
All	Mobilization of ions	Weakening and dissolution	Stone, concrete, mortar
Organic acid producers, e.g., fungi	Chelation of constituent ions	Weakening and dissolution	Stone, concrete, mortar
Algae, cyanobacteria	Uptake of H^+ ions by cells	Alkaline corrosion	Stone
All	Release of polyols (e.g., glycerol, polysaccharides)	Disruption of layered silicates	Siliceous stone

2.4 Deterioration of Concrete Due to Microbial Activity

Colonization and growth of microorganisms in concrete elements causes significant aesthetic and structural deterioration. Bacteria, cyanobacteria, fungi, lichens, and algae are among the most typical microorganisms that colonize, create biofilms, and affect construction materials' surfaces adversely (Gaylarde et al. 2003; Sand 1997). The first research study that proved that concrete surfaces could be deteriorated by microbial activity was performed in 1945 by C. D. Parker. Unlike previous research studies that failed to provide substantial evidence for the causes of corrosion of concrete surfaces in sewer systems, this research was able to determine the cause of concrete deterioration. Parker concluded that the deterioration of concrete in the inner side of sewer pipelines was caused by sulfuric acids produced by a bacteria (*Thiobacillus Concretivorus*) present on the concrete surface. This bacterium absorbs the hydrogen sulfide typical of a sewer environment (H_2S) and transforms it into the corrosion-causing sulfuric acid (H_2SO_4). Parker created an apparatus to expose concrete blocks to an enriched atmosphere of H_2S and NH_3 as shown in Figure 10.

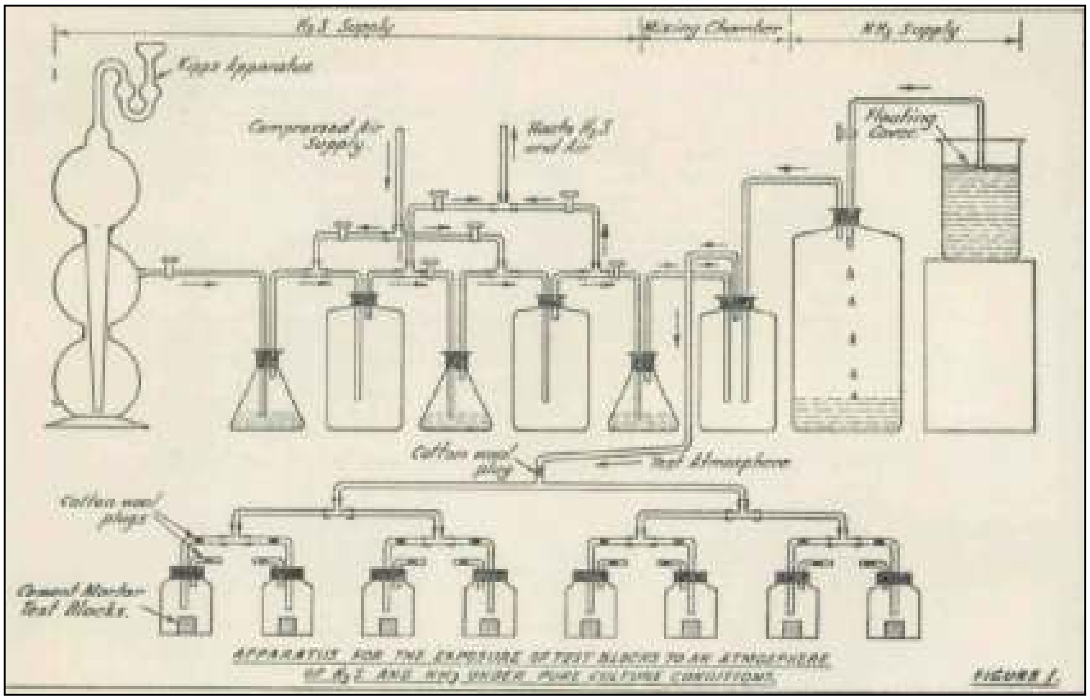

Figure 10
Laboratory test performed by Parker to test the effects of the bacterium on concrete (Parker 1945).

Using the laboratory setup presented in Figure 10, concrete blocks were inoculated with specimens found in corroded concrete inside sewer pipes for a period of 3 to 4 months until the corrosion was visibly evident as shown in Figure 11. This research provided evidence that demonstrated that more investigation on microorganisms and their deteriorating effects on concrete surfaces are needed.

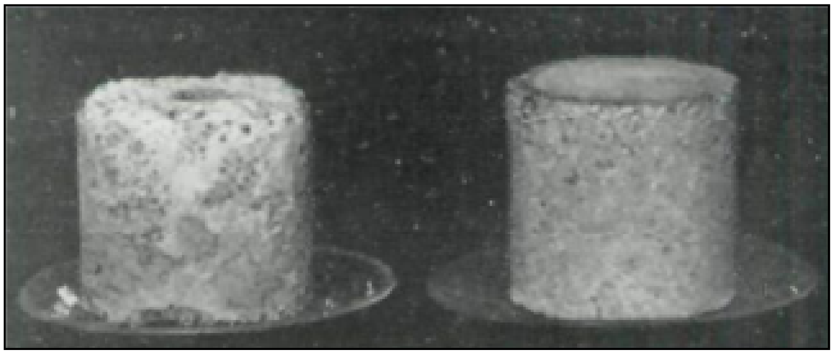

Figure 11
Corroded concrete block after removal of corroded material (Parker 1945)

Concrete elements under the effects of microorganisms for a prolonged time can show significant staining and weight loss that can be a threat to both their aesthetic and structural integrity (Parker 1945; Sand and Bock 1991). Sand and Bock also conducted laboratory-controlled experiments trying to quantify the amount of deterioration in the form of loss of material produced by isolated bacteria strains. The bacteria strains were collected from corroded concrete of sewer pipes. Concrete blocks were exposed to an H_2S rich environment inside a chamber, and sprayed with the isolated bacteria strains (T. intermedios/novellus, T. neapolitanus, T. thiooxidans) for a period of 9 to 12 months. The results of the experiment showed that the highest damage to concrete was caused by the strain T. thiooxidans, which in one of the experiments resulted in a medium value of 3.3% of material loss. However, these experiments simulated the conditions where concrete is exposed to a sewer-like environment, which is different from the one that highway infrastructure is exposed to in outdoors.

2.5 Deterioration of Highway Infrastructure Concrete Elements Due to Presence of Micro-Organisms

Gu et al. demonstrated the effects of fungi on the degradation of concrete (Gu et al. 1998). In this experiment, concrete samples were inoculated with *Fusarium* sp. (fungal specie) and *T. intermedius (bacteria).* During the first month of inoculation, the Portland cement samples demonstrated similar Ca^{2+} release for both species. For the remainder of the experiment, the concrete inoculated with Fusarium sp. showed higher levels of calcium release with 24% of weight loss compared to the 18% weight loss of the concrete inoculated with T. intermedius as shown in Figure 12. This experiment was the first to show that biofilms composed by, not only bacteria, but also fungal species have deteriorating effects on concrete. Furthermore, it showed how significant the weight loss of concrete elements can be when exposed to microorganisms.

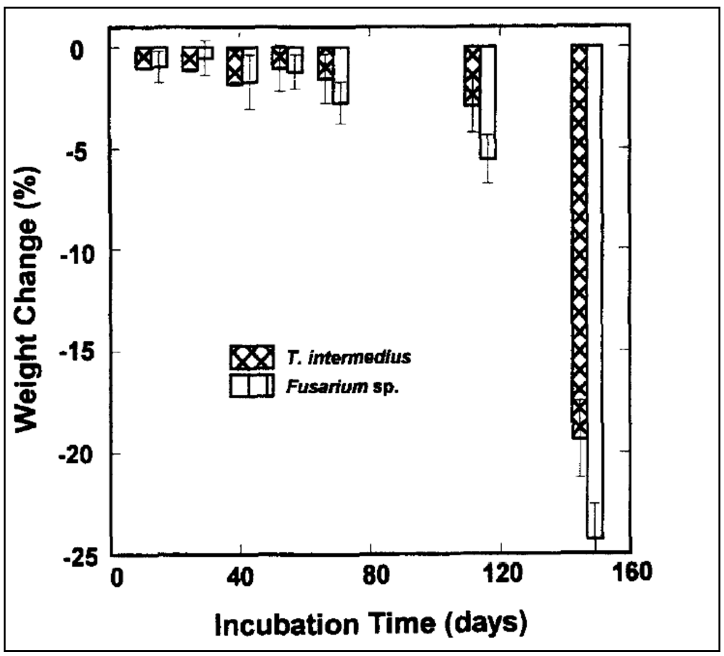

Figure 12
Percentage of weight change of concrete blocks inoculated with Thiobacillus intermedius and Fusarium sp. (Gu et al 1998)

Surface roughness, water to cement ratio, and photocatalytic TiO_2 cement mixtures have been identified as important parameters that influence bioreceptivity of concrete (Guillitte and Dreesen 1995; Giannantonio et al. 2009a; Dubosc et al. 2001). Bioreceptivity of concrete has been shown to increase as the surface roughness increases. Guillite and Dreesen conducted an experimental program to test different construction materials including aerated concrete, gobertange stone, modern mortar, brick, and petit granite as shown in Figure 13.

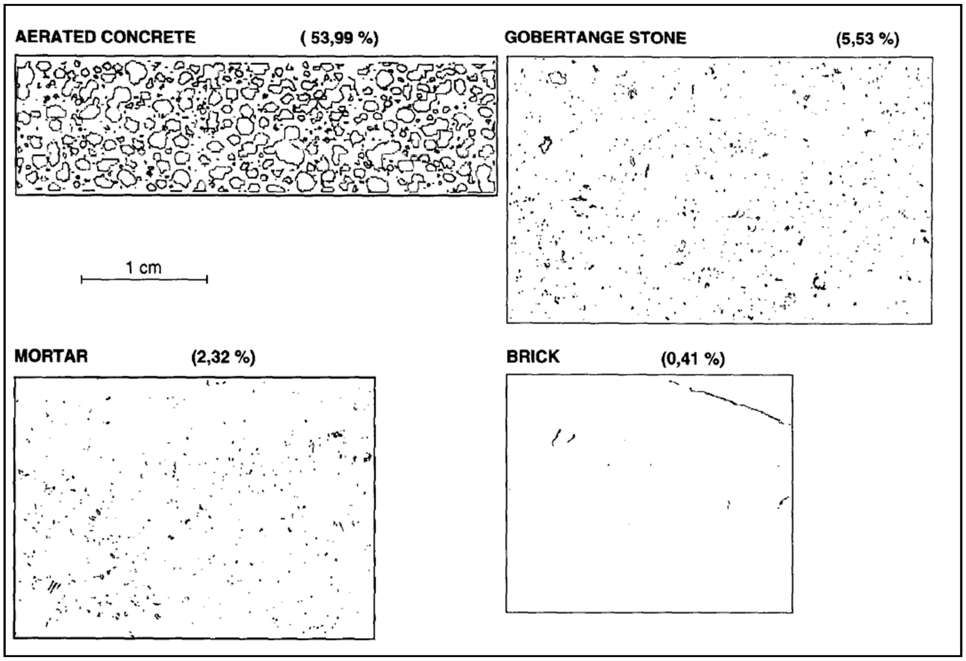

Figure 13
Macro-porosity values in percentage of the materials tested in the experiment. The values were obtained through automated image analysis (Guillitte and Dreesen 1995)

The experiment was conducted to test the bioreceptivity of these materials to microorganisms. Results showed that the construction materials with the highest porosity had the highest bioreceptivity (Guillitte and Dreesen 1995). Similarly, the vegetative cover of the construction materials after a period of 6 months was found to be higher in the materials where the porosity was higher as shown in Table 6.

Table 6
Percentages of vegetation coverage on the tested construction materials (Guillitte and Dreesen 1995)

Material	Aerated Concrete	Gobertange Stone	Modern Mortar	Brick	Petit Granit
Macroporosity Values (%)	53.99	5.53	2.32	0.41	Less than 0.1%
Maximum Vegetation Cover	100	100	60	60	30
Mean Cover	93±7	82±19	53±15	38±25	5±9

Another study investigated how the percentage of the covered area varied with porosity and water cement ratio. Results are shown in Figure 14 (Dubosc et al. 2001).

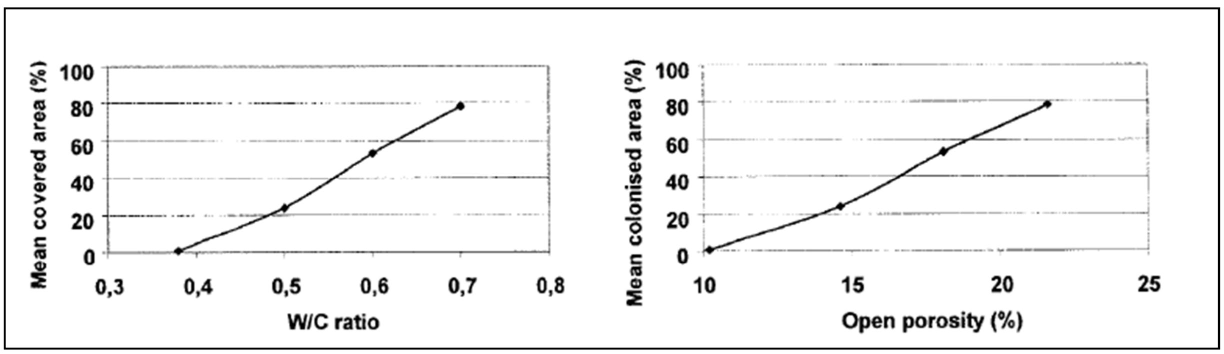

Figure 14
Percentage of mean covered area vs. water-to-cement ratio (left) and open porosity (right) (Dubosc et al. 2001)

As surface roughness of concrete increased, void ratio also increased creating more space for water retention, which can support microorganism growth. In addition, water/cement ratio has been proved to influence the bioreceptivity of concrete to certain deteriorating species of microorganisms. As the water proportion in a concrete mix increased, the permeability of concrete also increased; thus resulting in larger areas for moisture and nutrient retention (Giannantonio et al. 2009a; Dubosc et al. 2001).

A similar relation was observed in the experiment conducted by Giannantonio (Giannantonio et al. 2009a) and is shown in Figure 15. The coverage of the biofilm layer increased as the water-to-cement ratio increased.

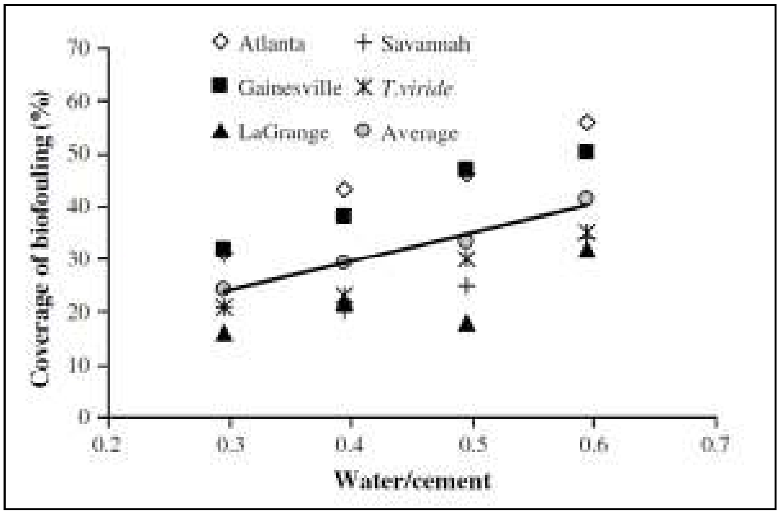

Figure 15
Coverage of Biofouling vs. water-to-cement ratio (Giannantonio et al. 2009a)

A research performed by Trejo et al. (Trejo et al. 2008) investigated the causes of deterioration on the concrete surfaces of bridges in Texas. The deterioration on these bridges was found in forms of large stains, black crusts, and deterioration of the concrete surface. At first, the deterioration was attributed to the influence of acidic waters near and in contact of concrete bridges' parts. However, after an investigation of the waters surrounding the bridges was conducted, the study discarded that the waters were responsible for the deterioration because they showed normal acid levels and concluded that the deterioration in the concrete was caused by the presence of microbes in the concrete surface. The study also revealed that the damage caused was proportional to the quantity of microbes present as shown in Figure 16, and that the microbe species present were, in fact, producing the acids that caused the deterioration (stains). The study recommended further investigation to determine the rate of deterioration of concrete attacked by microbial species and procedures and techniques to mitigate this attack (Trejo et al. 2008).

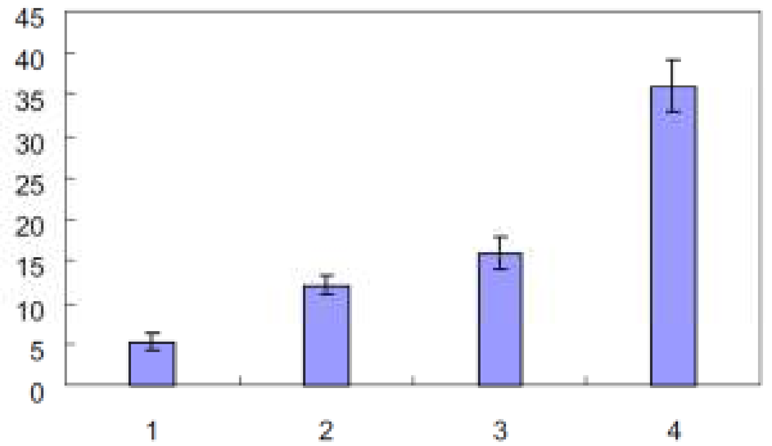

Figure 16
Concrete deterioration state versus quantity of microbes present in x10^6 cells/g (1 - undeteriorated concrete, 2 - slightly deteriorated, 3 - moderately deteriorated concrete, and 4 - severely deteriorated concrete) (Trejo et al. 2008)

2.6 Cleaning and Prevention Methods of Biofouling

Preventing and cleaning microbial growth in construction materials has always been a challenge. It is especially difficult to determine the best and most effective methods to prevent or control, and clean microorganisms present on concrete surfaces, given the broad variety of species and their specific characteristics. The prevention or cleaning method will often depend on the physiology of the microorganisms' variety colonizing the concrete. Moreover, controlling biofilms growth on highway infrastructure is even harder, since it is virtually impossible to control humidity in the environment and this is one of the most important factors that influence microorganism growth.

This report classifies control and cleaning methods as methods to eliminate microbial growth into three groups: *cleaning, eradication, or prevention. Cleaning and eradication* methods are used to eliminate microbial activity from surfaces were biofilm growth have already been established. *Prevention methods* are used for surfaces free from microbial activity to prevent, control, or minimize biofilm growth.

2.6.1 Cleaning Methods of Biofilms

Biofilms can be removed from their substrate by implementing mechanical procedures to detach microorganisms. These methods are the most recommended methods to eliminate biofilms because by successfully applying these methods, there is no need to use chemicals such as biocides that can have strong negative effects on health and environment. Furthermore, microorganisms such as mold (dead or alive) can be allergenic; that is why they still have to be removed after killing them with biocides (U.S. Environmental Protection Agency 2012). Methods that can be used in order to remove biofilms from concrete include blasting methods, which include soda blasting, dry ice blasting, and sand blasting, and other methods such as pressure washing, and scrubing or brushing of the concrete surface. Blasting methods are also known as abrasive methods. These methods clean materials and surfaces by removing the contaminants settled in them, and also removing a small percentage of the layer of the substrate.

2.6.1.1 Sandblasting

Abrasive blasting shown in Figure 17 is commonly known as *sandblasting.* This is a process that consists in propelling a stream of abrasive materials towards a given surface at high pressure in order to clean it from contaminants, remove paints and coatings, smoothen or roughen the surface, or even shape it (American Society for Testing and Materials 1997). Compressed air or centrifugal wheels are the most common mechanisms to propel the blasting media. There are several variants of this process, such as shotblasting; which uses copper, zinc, aluminum, and steel as the blasting medium, dry ice blasting; which employs CO_2 pellets, bead blasting; which uses glass particles as the blasting medium, sandblasting; which employs sand (silica) as the blasting method, but has been related to lung problems, and soda blasting; which uses Sodium Bicarbonate ($NaHCO_3$) as the blasting media.

Figure 17
Abrasive Blasting (Eye On Sandblasting & Painting Ltd.)

2.6.1.2 Soda Blasting

Soda blasting shown in Figure 18 is an abrasive but gentle cleaning method that is increasing in popularity. The process involves the use of Sodium Bicarbonate ($NaHCO_3$) as the cleaning medium, applied against a surface using compressed air. This method is very effective for cleaning surfaces, paint stripping, automotive restoration, industrial equipment maintenance, rust removal, graffiti removal, masonry cleaning, and boat hull cleaning. Soda blasting became very popular in the early 1980s when it was selected by the engineers of the state of New York to clean the Statue of Liberty without causing any harm to its exterior. Other methods such as sand blasting were discarded because they could cause damage to the materials of the Statue of Liberty (Pickard 2012).

Figure 18
Soda blasting of a steel container prior to repainting (Mid atlantic sods dry ice blasting 2012)

The equipment used to perform soda blasting operations is called soda-blaster and is shown in Figure 19. The soda-blaster consists of a blast generator, high pressure compressed air, moisture decontamination system, blast hose, and a blast nozzle (Pickard 2012).

Figure 19
Soda Blasting Machine (Maine Soda Blasting)

2.6.1.3 Dry Ice (CO_2) Blasting

Dry ice blasting shown in Figure 20 uses CO_2 as the blasting medium. Carbon dioxide shown in Figure 21 is a non-poisonous, liquefied gas, which is relatively cheap when compared to the other blasting materials. One of the advantages of this method is that it is environmentally- friendly, and contains no secondary contaminants such as solvents or grit media, which can be found in other blasting materials (ColdJet).

Figure 20
Dry-Ice blasting process (Pure Air Systems 2012)

Figure 21
Dry-Ice blasting medium (pellets)
(American Society for Testing and Materials 1997)

2.6.1.4 Pressure Washing

Pressure washing shown in Figure 22 is a method that is used in order to remove contaminants from surfaces. The process consists in pumping water at high pressures against a surface to remove dirt, paint, coatings, or any other undesired loose particles. It is a common practice for highway maintenance agencies to implement this method in order to clear their roads and bridges from debris, dirt, grease, and contaminants. The New York State Department of Transportation employs this cleaning technique in their bridges and roads to either clean the surface, or to prepare the surface for the application of sealants or coatings (New York State Office of Structures 2007; NY Office of Transportation Maintenance 2008)

Figure 22
Pressure washing of a concrete deck (NY Office of Transportation Maintenance 2008)

2.6.2 Eradication Methods

The following methods have been proved to be effective in some industries and consist in eliminating the living microorganisms from their substrate by employing different means.

2.6.2.1 Biocides

The most common method of killing microbial life is by the application of biocides - (bio: life form; cide: killer). Biocides are a versatile solution because it comes in many forms such as liquid, powder, gas. Generally, gas or vapor biocides are used to decontaminate materials that have already been colonized by microorganisms. Liquid and powder forms are often used to prevent their growth (e.g. quaternary ammonium compounds are constantly used in pools to prevent the growth of algae). Biocides are effective chemicals that eliminate and prevent microbial growth because of their broad variety, intensity, and spectrum (Bott 2011). However, these chemicals can be dangerous for humans and animals, which is why precautions have to be considered before selecting the biocide:

- Spectrum of the biocide. It is important to determine the kind of microorganisms that are causing the deterioration. Some biocides have specialized effect on a specific type of microorganism such as bacteria or algae. Other biocides have a broader spectrum and can attack a larger variety of microorganisms but it is always important to make sure that the microorganisms responsible for the deterioration are going to be targeted by the biocide that is going to be applied.

- Toxicity of Biocide**s.** Biocides are toxic products designed to kill life forms, and depending on the biocide, they can be dangerous for humans, animals, and plants. When planning to use biocides in places that can represent a threat to human or animals, the level of toxicity must be considered.

- Effect on materials. The biocide chosen must not change any property of the material on which it is going to be applied. Some biocides can corrode steel, change the color of certain surfaces and deform plastics.

There are many different kinds of biocides used for cleaning. Some of the most common biocides used for cleaning materials are composed by the following chemicals: oxidizing agents, aldehydes, alcohols, phenolics, organic acids, Quaternary ammonium/phosphonium compounds, and Isothiazolinones. The use of the biocide and its characteristics will vary depending on which chemical compound they contain (Allsop 2004).

- Oxidizing agents. One of the most common oxidizing agents is chlorine. This compound has been used for many years in both the domestic and industrial world, mainly because of its low cost. Other oxidizing agents are ozone, hydrogen peroxide, and other halogens. Ozone has become very popular in the water supply industry where it is used to purify potable water.

- Aldehydes. These compounds have good water solubility and vaporize well. Among them, Formaldehyde and Glutaraldehyde have broad spectrums. Glutaraldehyde is commonly used in the medicine industry to clean and disinfect surgical equipment.

- Alcohols. These chemicals are broadly used for hand-disinfectant lotion because of their effects on bacteria and viruses. However, these chemical evaporate very quickly and are not commonly used as biocides.

- Phenolic. These compounds were some of the first effective biocides. Usually, these biocides target bacteria, but some variations of phenolic compounds can be used to target fungi as well. Some phenolic compounds have very strong odor and some others are very persistent in the environment, which is why their use is limited.

- Organic Acids. Weak organic acids as acetic, propionic, lactic, sorbic, and benzoic are often used in the food industry as preservatives and to prevent the growth of molds and yeasts in fruit juices and fermented milk products.

- Quaternary ammonium/phosphonium compounds. These chemicals have a broad spectrum as biocides when not used in combination with anionic surfactants, and high levels of protein and salts, which decrease their effects. One of the best characteristics of these compounds is that they can be used as long-term biocides.

- Isothiazolinones. These chemicals are one of the newest technologies in biocides. Isothiazolinones are commonly used as dry-film preservatives in paints, adhesives, sealants, and plastic films.

Table 7 presents information on how different biocide compounds such as chlorine, hypochlorite, phenols, izothiazolinones, etc. affect microbial activity. Different biocides have different modes of action in order to eradicate microbial activity. These modes of action range from oxidizing actions, which destroys cell walls; membrane active components, which affect membrane integrity; and a number of microbial processes inhibitors that restrict a vital process of the microorganism eventually resulting in death.

Table 7
Mechanism of action of Biocides (Allsopp 2004)

Compounds	**Mode of Action**
Hypochlorite, bromine, Ozone.	**Oxidizing**, eliminates cells' walls and constituents
Quaternary ammonium compounds, alcohols, parabens.	**Membrane active**, affects transport mechanisms and affects membrane integrity
Phenols, adehydes, formaldehide, condensates, and parabens.	**Protein denaturation**
Izothiazolinones, bronopol, dibromodicyanobutane.	**Protein synthesis inhibitor,** bind with thiol groups in cell affecting enzyme activity
IPBC, carbendazim.	**Nuclear division inhibitor,** DNA synthesis inhibition
Diuron, irgarol, terbutryn.	**Photosynthesis Inhibition,** affects electron transport

2.6.2.2 Physical Methods

Physical methods are used in order to eradicate microbial life. In the housing industry, it is a common and recommendable practice to control humidity in places where mold growth is developing in order to restrict its growth. As discussed in previous sections, biofilms start to develop when enough humidity and temperatures ranging from 25 to 30°C are available (Bastidas-Arteaga et al. 2008). However, it is virtually impossible to control these parameters outdoors.

To eliminate biofilms in industrial equipment it is very common to implement variations to pressure and temperature. Usually, these variations are implemented in closed elements and equipment such as pipelines and boilers where they are easy to control (Bott 2011; Allsopp et al. 2004). UV rays, microwaves and gamma rays have also been employed in order to restrict microorganisms' growth (Bott 2011; Allsopp et al. 2004). Gamma radiation has also been successfully implemented to eliminate fungal growth from books after flooding events (Allsopp et al. 2004).

Even though, physical methods have been successfully applied in certain industries and fields, it is unlikely that these methods would be possible to succeed in highway infrastructure, because it is virtually impossible to control variables such as temperature, humidity, and pressure for long periods of time in outdoors. UV rays, gamma rays, and microwaves will also show negative results because of the difficulty of the application of these techniques in open environments and also because of the magnitude of the size of highway infrastructure elements.

2.6.3 Preventive Methods

New technologies on prevention of microorganisms' growth are currently being explored. The use of Titanium Dioxide (TiO_2) and zeolite compounds as additives in the concrete mix have been shown to reduce the growth and development of biofilms in concrete elements (Kurth 2008; Sanchez-Silva and Rosowsky 2008).

2.6.3.1 Titanium Dioxide Photocatalyst Coating

Titanium dioxide can be used to construct surfaces that are capable of self-cleaning when irritated with UV from sunlight and washed by rainwater. TiO_2's self-cleaning ability is a result of a combination of the photo induced super-hydrophilic and photocatalytic properties of the material (Fujishima and Zhang 2006). Super-hydrophilicity is defined as the ability of the material to have a water contact angle of approximately 0^o while photocatalysis is defined as the ability of the material to decompose pollutants when irritated by UV light. In this process, bacteria and organic build is decomposed by photocatalysis while dust and organic contaminants are washed away by rain by the photo induced super-hydrophilicity as shown in Figure 23. Both processes take place simultaneously on the TiO_2 surface. The following section explains the mechanism behind both processes.

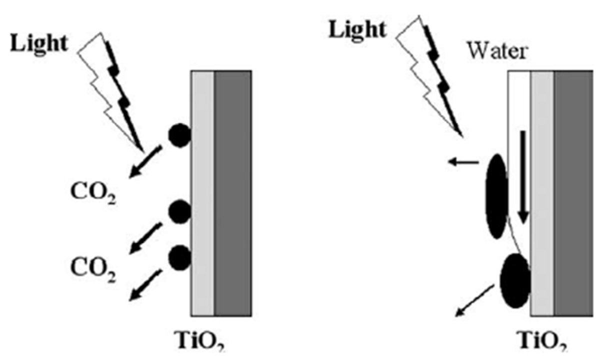

Figure 23
Super-hydrophilic process of TiO2 (Fujishima, A., & Zhang 2006)

2.6.3.1.1 Photo induced super-hydrophilicity

The anatase form of TiO_2 is considered to be a super-hydrophilic (hydro: water; philic: attraction) component when exposed to UV light. When irradiated by UV light, very low contact angles (approximately 0o) between water and supporting solid is obtained (Figure 24). This causes the water droplets to behave as a layer or a sheet, instead of individual circular droplets as shown in Figure 25.

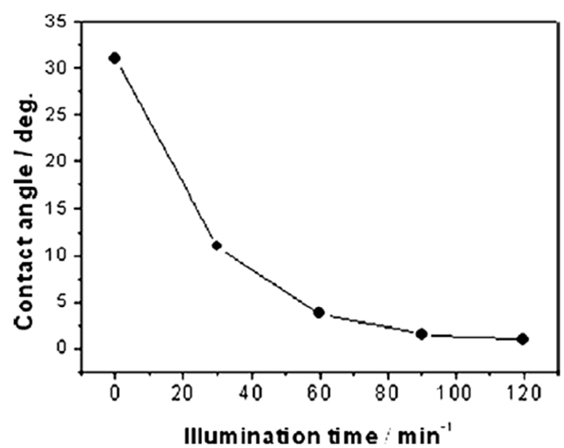

Figure 24
Water contact angle as a function of time under UV illumination (Fujishima, A., & Zhang 2006)

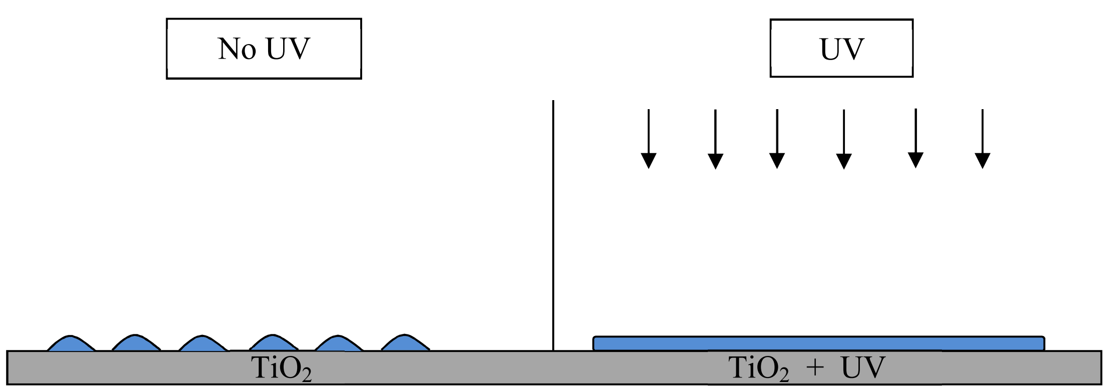

Figure 25
TiO_2's super-hydrophilicity

Since TiO_2 is a semiconductor with a bandgap of about 3.0 eV, it produces electrons and holes when exposed to UV light (Fujishima et al. 2000):

$$TiO_2 + 2h\nu \longrightarrow 2e^- + 2h^+ \quad (1)$$

The electrons released reduce Ti^{4+} cations to a Ti^{3+} state and the holes oxidize O^{2-} anions releasing oxygen atoms and creating vacancies in the titanium dioxide lattice structure as shown in Figure 26:

$$Ti^{4+} \longrightarrow Ti^{3+} + e^- \quad (2)$$

$$4h + 2O_2^{2-} \longrightarrow O_2 \quad (3)$$

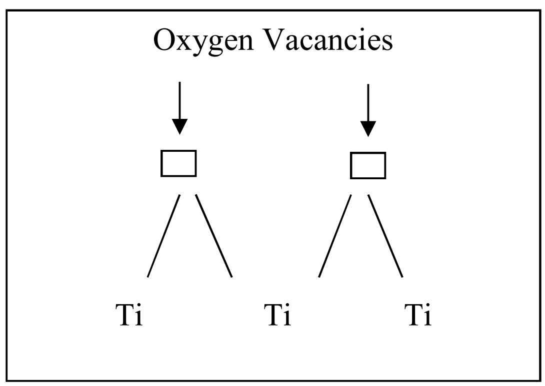

Figure 26
TiO_2's super-hydrophilicity (Part I)

When the surface is washed, water molecules occupy these vacancies as shown in Figure 27 producing adsorbed OH groups and making the surface hydrophilic.

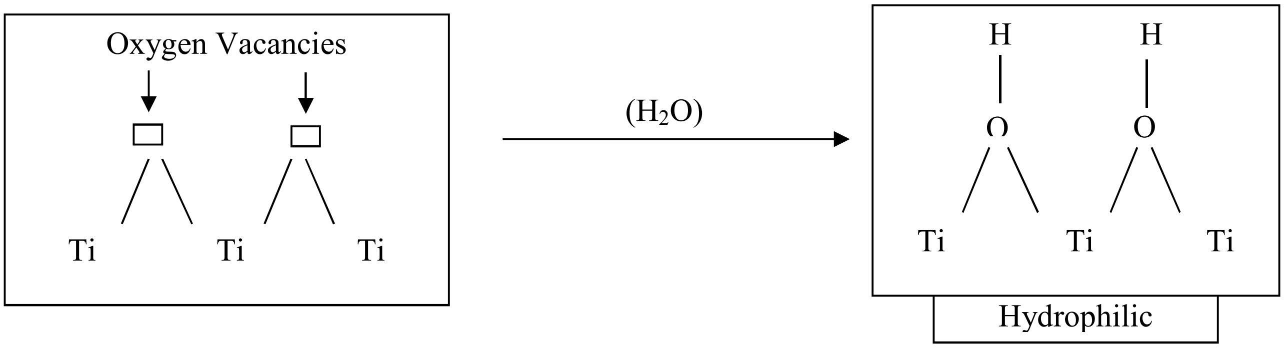

Figure 27
TiO_2's super-hydrophilicity (Part II)

2.6.3.1.2 Heterogeneous Photocatalysis.

Heterogeneous photocatalysis accelerates the natural decomposition process of harmful air pollutants and organic compounds. Photocatalytic reaction starts with the formation of electron-hole pairs initiated by energy that is greater than the band gap energy as previously described in photo induced super-hydrophilicity. Once irradiated with UV light, titanium dioxide forms highly oxidizing holes and photo-generated electrons resulting in hydroxyl radicals and superoxides, respectively (Fujishima and Honda 1972):

$$TiO_2 + hv \rightarrow h^{+} + e^{-}$$

$$OH^{-} + h^{+} \rightarrow OH^{*}$$

$$O_2 + e^{-} \rightarrow O_2\text{-}$$

The holes, h+, and the electron pair, e-, are the produce of powerful oxidizing and reductive agents (Shao and Yang 2003). The hydroxyl radicals and superoxides have been proven to play an important role in the photodegradation reactions (Fujishima and Honda 1972). The hydroxyl radicals, OH*, are strong oxidants that rapidly decompose organic and inorganic compounds, while the superoxide ions, O_2- , are the reduction pathways (Hunger et al. 2008).

Thus, rather than just absorbing pollutants, common of traditional air purification methods, pollutants are decomposed to nonhazardous waste products with little energy requirements (Fujishima and Honda 1972).

2.6.3.1.3 Photocatalytic and self-cleaning performance of TiO_2 surfaces.

A number of studies have been carried out in order to test the self-cleaning and photocatalytic properties of TiO_2 in construction materials. Giannantonio et al. 2009, conducted a study to describe the fouling of concrete surfaces by diverse fungal genera, extracted from existing contaminated concrete surfaces. In their study, they examined how different fungal genera could affect different types of concrete compositions, surface finishes, and water-to-cement ratio. The sampling for the microorganisms to be used in their experiment was performed in four outdoor concrete sites in Georgia. The sites sampled showed typical fouled concrete characteristics such as black crusts covering large sections of the concrete surface. Mortar tiles of 6 x 6 x 0.4 cm with variations in cement composition, water-to-cement ratio, supplementary cementing material (SCM) additions, and surface finishes, were prepared in order to determine the susceptibility of different types of concrete to microbial growth. The variations of the mortar tiles were prepared as follows: one standard mix containing Holcim GU I/II cement with no SCM addition and brushed surface, three tiles with Holcim GU + limestone, Essroc I/II, and Essroc I/II + TiO_2 cement respectively, three tiles with water-to-cement ratio of 0.3, 0.4, 0.6 respectively, ten tiles with SCM additions of fly ash: 10-18-25 in percentage, slag: 10-25-50 in percentage, silica fume: 5-10-15 in percentage, metakaolin: 8% respectively, and two tiles with polished surface finishes of 120 grit and 600 grit, respectively.

All the mortar tiles were inoculated with the fungal media collected and placed inside previously sterilized incubation chambers. The inoculated tiles were sprinkled with a nutrient substance to simulate outdoor environmental conditions. After the controlled laboratory experiment was carried out, most of the tiles showed biofouling characteristics. A strong statistical relationship between water-to-cement ratio and the coverage of biofouling was observed. The tiles with water-to-cement ratio of 0.3 showed significantly lower coverage of the biofouled area than those with water-to-cement ratio of 0.6. These results suggest that concrete structures with lower water-to-cement ratios are less susceptible to biofouling, which also agrees with the results obtained by Dubosc et al. in 2001.

The mortar tiles with photocatalytic TiO_2 addition showed a strong resistance to the colonization of microorganisms when compared to a tile with the same cement composition and same inoculated genera, but without TiO_2. The results of this experiment suggest that the use of photocatalytic cements in construction materials may prevent and mitigate the biofouling of the concrete surfaces.

As previously mentioned, application of biocides is among the most common methods to eliminate microbial life (Bott 2011; Allsopp et al. 2004). A research performed by Fonseca, A. et al. (Fonseca et al. 2010) compared three products; the use of two conventional biocides, Biotin T®, commonly used for cleaning monuments, and Anios D.D.S.H®, another common biocide used as an antiseptical product in hospitals, and TiO_2 in its anatase form. Laboratory experiments and in-situ experiments were implemented in order to determine the anti-microbial effects of the three products selected.

For the laboratory tests, mortars were manufactured using Portland cement and lime, and the mortars containing TiO_2 were prepared using the same specifications but adding nanocrystaline anatase powder to the mix. After preparation, all mortars were inoculated with a photosynthetic culture and incubated for a period of four months to ensure biological growth. Afterwards, the mortar slabs without TiO_2 were treated with the two evaluated biocides. Finally, two weeks after, all mortar slabs were analyzed in order to quantify the amount of microbial life present.

The in-situ experiments were performed in two external walls of the *Palacio Nacioanal da Pena (Sintra)*. The two external walls selected showed extensive colonization by a diverse community of microorganisms. After the two locations were selected, the three products analyzed were brushed and sprayed against the biofouled walls on small areas of 50 cm^2. After the experiment was conducted and both the experimental mortar slabs and the treated surfaces on the in-situ site were analyzed to quantify microbial life present, the best results were obtained in both cases by the surfaces and slabs containing TiO_2.

2.6.3.2 Zeolite compounds

Haile and Nakhla tested the inhibitory effect to microorganism growth of zeolite compounds as coatings for concrete (Haile and Nakhla 2010). The experiment consisted of inoculating concrete tiles with an isolated bacterium (Th. Thiooxidans). The concrete tiles were coated with antimicrobial zeolite, and as control uncoated tiles and blank zeolite coated tiles without antimicrobial agent were used. The concrete tiles were immersed in a basal nutrient medium with th. Thiooxidans. In order to determine the antimicrobial properties of zeolite coatings on concrete, dry cell unit weight (to quantify the increase in the number of microorganisms), and solubilization of metals in the cement paste were measured. SEM images of the concrete specimens were taken before and after the inoculation with the bacterium as shown in Figure 28.

Images A, B, and C in Figure 28, correspond to concrete tiles without zeolite coatings before (A) and after (B and C) exposure to the bacterium. The deterioration of the concrete surface of these specimens after exposure is visible (B, C). Concrete specimens coated with both antimicrobial zeolite and blank zeolite, demonstrated the resistance of zeolite to bacterial induced corrosion (images D, E, F, G, H). It was concluded from this experiment that concrete specimens with zeolite coatings are resistant to bacterial induced corrosion by th. Thiooxidans.

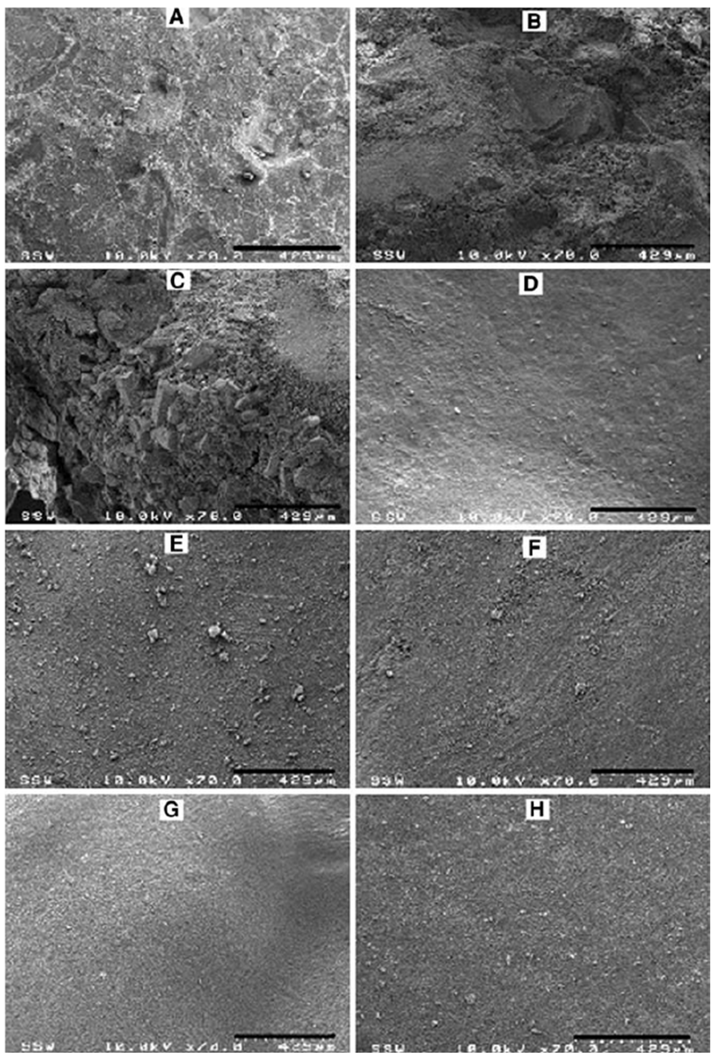

Figure 28
SEM images of concrete tiles. A, B, and C: concrete tiles without zeolite coatings. D, E, and F: concrete tiles coated with zeolite without antimicrobial agent. G and F: concrete tiles coated with antimicrobial zeolite (Haile and Nakhla 2010)

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CHAPTER 3 -BEST PRACTICES FOR PREVENTATIVE MAINTENANCE AGAINST MOLD AND MILDEW GROWTH OF CONCRETE BRIDGE ELEMENTS

3.1 Introduction

The development of biofilms on concrete structure (layer of mildew, mold, bacteria, fungus, yeasts or any combination) has a negative impact not only due to aesthetic reasons but also due to its influence on the performance and integrity of the structure (Adamo and Violante 2000; Bastidas-Arteaga et al. 2008; Bott 2011; de la torre et al. 1992). Biofilms develop easily when the right conditions are present, such as high relative humidity (60 to 98%) and temperature (70 to 95°F). These conditions are encountered in the hot-humid climatic region, which includes the state of Louisiana (Department of Energy 2010). As a consequence, visible stains and a relatively fast deterioration of bridges, roads, highways, and other structures are encountered in Louisiana. This issue has triggered public complaints, which as a result have supported the need to find a practical and economic solution to be adopted by the Louisiana Department of Transportation and Development (LADOTD) to address biofilm issues. Figure 29 (a and b) presents concrete elements in Louisiana that show clear signs of biofilm activity, characterized by the black stains.

(a) (b)

Figure 29
Biofilm Sites in Louisiana

Current methods for cleaning and eliminating biofilm development on highways and bridges include pressure washing, sweeping, brushing, sand blasting, dry-ice (CO_2) blasting, and soda blasting, but these methods have shown poor results since biofilms continue to develop in the structures in short periods of time (Ray and Hanks 2012). Furthermore, constantly treating highways and bridges would be economically unsustainable given the large extent of the work to be performed, the equipment and personnel needed to accomplish these tasks, and the safety of workers during cleaning. Therefore, there is a critical need to identify a more practical alternative than currently available mechanical and periodical cleaning methods.

Several methods for dealing with biofilm issues have been suggested in the literature (Ray and Hanks 2012; Allsopp et al. 2004, Bott 2011; Kurth 2008; Giannantonio et al. 2009). These methods include the use of chemicals and physical controls such as biocides (oxidizing agents, aldehydes, acids, chlorine, etc.), pressure control, temperature control, humidity control, UV rays, titanium dioxide (TiO_2) photocatalyst, and zeolite compounds to treat biofilm development. However, the application of chemical compounds to the entire system could be cost-prohibitive and environmentally damaging (Ray and Hanks 2012; Allsopp et al. 2004). The objective of this study is to present a detailed review of successful methods and practices currently used to prevent and eliminate biofilm development on concrete surfaces. These baseline data are currently used by LADOTD to establish a maintenance protocol against biofilm in the state. To achieve this objective, a survey of current DOTs practices with respect to adopted cleaning and prevention methods was conducted. Further, an economic analysis between the most common methods was conducted to determine which method is the most suited for the transportation industry in terms of safety, performance, durability, and cost.

3.2 Background of Concrete Biodeterioration

Concrete biodeterioration was reported in 1945 by Parker, who investigated the extensive corrosion process that was developing in concrete walls inside sewage systems. This research was the first laboratory investigation that linked microorganisms to concrete deterioration. Since then, several investigations have been conducted demonstrating the adverse impacts of microorganisms on concrete elements under different microbial species and conditions. Gu et al. (1998) demonstrated the effects of fungal and bacterial species on concrete. This research demonstrated and quantified the weight loss, which translates in deterioration of concrete samples incubating microorganisms. Guillite and Dreesen in 1995 evaluated the biodeterioration of different construction materials (aerated concrete, gobertange stone, modern mortar, brick, and petit granite) by measuring the difference in bioreceptivity. The authors concluded that materials like concrete and aerated concrete are more susceptible to biofilm development because of their high porosity when compared to materials with lower porosities such as granite (Tortora et al 2004). Other investigations have shown a direct correlation between water-to-cement ratio and biodeterioration (Mckinney 2009; Escadeillas et al. 2007; Parker 1945). These investigations have proved that the higher the water-to-cement ratio is, the more susceptible the concrete surface becomes due to an increased area for moisture and nutrient retention.

3.3 Cleaning and Preventive Methods

Two main categories of treatment methods have been identified for biofilm issues: cleaning methods and preventive methods (Ray and Hanks 2012). Cleaning methods are those employed to eliminate biofilm communities from concrete surfaces, while preventive methods focus on preventing initial colonization and reproduction of microorganisms on the concrete surface.

3.3.1 Cleaning Methods

Cleaning methods can be divided into two subcategories: mechanical methods and eradication methods. Pressure washing, sand blasting, soda blasting, dry-ice (CO_2) blasting, have all been shown to clean surfaces from biofilms. Eradication methods like biocides, UV rays, microwaves, gamma rays have been shown to kill or eliminate microbial life settled on surfaces (Bott 2011; Allsopp et al. 2004). These methods have been effective in eliminating biofilms; however, they have to be applied periodically in order to restrict the redevelopment of the biofilms *(6)*.

In industrial facilities, it has been a common practice to employ mechanical forces to remove biofilm from their sustaining surface. The most common methods are pressurized water, sand blasting, dry-ice blasting, and soda blasting. However, microorganisms invisible to the naked eye such as bacteria, which are commonly found in biofilm communities have a higher resistance to these methods and tend to regenerate and re-colonize the surface after such treatments have been applied, eventually leading to a full regeneration of the biofilm.

In highways and bridges maintenance activities, it has been a common practice to employ mechanical forces to “clean” stained concrete and remove dirt and debris from its surface. The most common method has been pressure washing. As previously mentioned, this method is effective in removing stains that are generally caused by biofilm development, dirt, and debris from surfaces. However, biofilm can redevelop in short periods of time after this method has been applied, since it does not completely remove all the microorganisms from the biofilm community. Furthermore, stronger environmental restrictions in some states, such as the final deposition of the water utilized for pressure washing, are making this method more difficult to employ, since water utilized to clean bridges and highways could be contaminated with chemicals that could represent a threat to water streams (NY Office of Transportation Maintenance 2008)

3.3.2 Preventive Methods

Preventive methods consist of the addition of certain compounds into the concrete mix or as surface coatings such as TiO_2 and zeolite to restrict the colonization and growth of microorganisms on the concrete surface. Results have shown that these compounds prevent biofilm proliferation. Recent research proposed the use of compounds such as zeolite and TiO_2 in the concrete mix to control the growth and reproduction of biofilm communities on concrete structures (Haile et al. 2010; Giannantonio et al. 2009). TiO_2 can be used to construct concrete surfaces that are capable of self-cleaning when irradiated with UV from sunlight and washed by rainwater. TiO_2's self-cleaning ability is a result of a combination of the photo induced super-hydrophilic and photocatalytic properties of the material (Fujishima & Zhang 2006). Kurtis investigated the resistance of concrete tiles with TiO_2 to biofilm development. A set of control concrete tiles were compared to tiles prepared with TiO_2-cement. Both sets of concrete tiles were inoculated with commonly found fungal species found in biofilm communities and tested for a given period of time. After the experiment, the concrete tiles that contained TiO_2 showed a strong resistance to the proliferation of biofilm communities, while the typical concrete tiles showed a substantial coverage by biofilms.

3.4 Survey of State Practices

The current state of practices adopted by highway agencies to address biodeterioration was reviewed through a comprehensive survey. The survey was developed and conducted to collect information from all the states' highway agencies regarding bridge maintenance procedures for cleaning of concrete bridge structures. The survey also quantified how many states have encountered biofilm growth on concrete elements as is the case in Louisiana. Furthermore, the survey aimed at collecting information, from the states that have biofilm growth on concrete structures, on the maintenance process or processes implemented by these states to handle biofilms issues. The main questions in the survey were as follows:

- Number and approximate conditions of bridges in the state;
- Is there biofilm growth on concrete structures in your state?
- Is there a maintenance program to address this issue?
- If no, what is the reason for not treating it?
- What methods are currently being employed to address biofilm issues?

The survey was distributed nationwide following the climatic regions classification adopted by the Department of Energy. This climatic regions classification consists of eight different regions (Figure 30): Hot-Humid, Mixed-Humid, Hot-Dry, Mixed-Dry, Cold, Very Cold, Subarctic, and Marine.

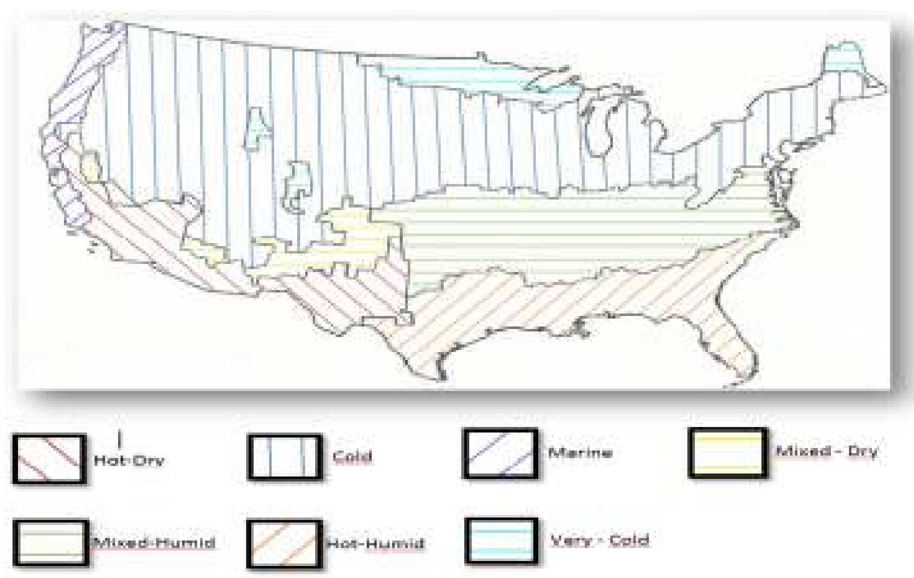

Figure 30
Climatic Regions (U.S. Department of Energy 2010)

To include a representation of all climatic regions, at least one response from each region was included. However, the subarctic climatic region was not included in the survey. Phone interviews with experts were also performed to collect additional information from state agencies.

3.5 Findings of the Literature Review

Findings of the comprehensive literature review, survey of state of practice, and phone conversations are presented in the following sections.

3.5.1 Biofilms Development and Impact on Concrete Elements.

Results of the literature review indicate that microorganisms of different types (bacteria, fungi, mold, mildew, algae, lichens, and protozoa) can colonize concrete surfaces and form biofilm communities (Bott 2011; Allsopp 2004; Kurth 2008). These biofilm communities are very diverse but they all have a need for nutrients that can be obtained from the substrate, on which the biofilm community is formed, from sunlight, from water or humidity, from the surrounding air, and/or from the biofilm community itself (Sanchez-Silva & Rosowsky 2008; Bastidas-Arteaga et al 2008; Kumar and Kumar 2009).

Biofilms have a detrimental effect on concrete structures due to the weathering of the surface. It was estimated that approximately 30% of the weathering of construction materials including concrete are caused by biological sources (DeGraef 2005; Sand 2001). The process by which biofilms affect concrete structures can be divided into three steps (Sanchez-Silva and Rosowsky 2008):

- Colonization and initial deterioration of concrete surface;
- Penetration of microorganisms into the concrete matrix; and
- Initiation and propagation of cracks within the concrete.

Immediately after construction, concrete elements have a low bioreceptivity due to the high levels of alkalinity (pH levels between 11 and 13). However, the interactions between the concrete element and CO_2 molecules present in the environment cause these high levels of alkalinity to drop, until it reaches levels that allow biofilms to colonize. After these levels are reached, different species of microorganisms start to colonize the surface creating biofilm communities. Biofilm communities excrete organic and inorganic acids that react with concrete, solubilizing cement components. Microorganisms then start to penetrate into the concrete matrix increasing the concrete porosity, which then changes concrete's coefficient of diffusion and internal conductivity. Therefore, corrosion of the steel reinforcement becomes easier for oxidizing and corroding agents present in the environment.

Surface roughness, water to cement ratio, and photocatalytic TiO_2 concrete mixtures have been identified as important parameters that influence bioreceptivity of concrete (Kurth 2008; Guillitte and Dreesen 1995; Dubosc 2011). The study conducted by Guillite and Dreesen tested different construction materials with different porosities to determine if porosity or surface roughness had a relationship to bioreceptivity. It was shown by this study that construction materials with higher porosities and surface roughness were easier for microorganisms to colonize. A study conducted by Giannantonio et al. (2009) *(14)*, showed that water-to-cement ratio and open porosity were important parameters in concrete bioreceptivity.

3.5.2 Cleaning and Prevention Methods for Biofilm Growth

This section summarizes the most common cleaning and prevention methods for biofilm growth identified in this study; additional details have been presented elsewhere (Hassan 2013). It is noted that the selection of prevention or cleaning methods will often depend on the physiology of the microorganisms' variety colonizing the concrete. Moreover, controlling biofilms growth on highway infrastructure is a major challenge, since it is virtually impossible to control humidity in an open environment and this is one of the most important factors that influence microorganism growth.

3.5.2.1 Cleaning Methods of Biofilms

Biofilms can be removed from their substrate by implementing mechanical procedures to detach microorganisms. These methods are the most common methods to eliminate biofilms because by successfully applying these methods, there is no need to use chemicals such as biocides that can have strong negative effects on health and environment. Furthermore, microorganisms such as mold (dead or alive) can be allergenic; that is why they still have to be removed after killing them with biocides (U.S. Environmental Protection Agency 2012). Methods that can be used in order to remove biofilms from concrete include blasting methods, which include soda blasting, dry ice blasting, and sand blasting, and other methods such as pressure washing, and scrubing or brushing of the concrete surface. Blasting methods are also known as abrasive methods. These methods clean materials and surfaces by removing the contaminants settled in them and also a small percentage of the layer of the substrate.

3.5.2.1.1 Sandblasting

Abrasive blasting, shown in Figure 31, is commonly known as *sandblasting.* This is a process that consists of propelling a stream of abrasive materials towards a given surface at high pressure in order to clean it from contaminants, remove paints and coatings, smoothen or roughen the surface, or even shape it American Society for Testing and Materials 2012). Compressed air or centrifugal wheels are the most common mechanisms to propel the blasting media. There are several variants of this process, such as shotblasting; which uses copper, zinc, aluminum, and steel as the blasting medium, dry ice blasting; which employs CO_2 pellets, bead blasting; which uses glass particles as the blasting medium, sandblasting; which employs sand (silica) as the blasting method, but has been related to lung problems, and soda blasting; which uses Sodium Bicarbonate ($NaHCO_3$) as the blasting media.

Figure 31
Sand and Soda Blasting

3.5.2.1.2 Soda Blasting

Soda blasting is an abrasive but gentle cleaning method that is increasing in popularity. The process involves the use of Sodium Bicarbonate ($NaHCO_3$) as the cleaning medium, applied against a surface using compressed air. This method is very effective for cleaning surfaces, paint stripping, automotive restoration, industrial equipment maintenance, rust removal, graffiti removal, masonry cleaning, and boat hull cleaning. Soda blasting became very popular in the early 1980s when it was selected by the engineers of the state of New York to clean the Statue of Liberty without causing any harm to its exterior.

3.5.2.1.3 Dry Ice (CO_2) Blasting

Dry ice blasting uses CO_2 as the blasting medium. Carbon dioxide is a non-poisonous, liquefied gas, which is relatively cheap when compared to the other blasting materials. One of the advantages of this method is that it is environmentally- friendly, and contains no secondary contaminants such as solvents or grit media, which can be found in other blasting materials (ColdJet 2011).

3.5.2.1.4 Pressure Washing

Pressure washing is a method that is used in order to remove contaminants from surfaces. The process consists of pumping water at high pressures against a surface to remove dirt, paint, coatings, or any other undesired loose particles. It is a common practice for highway maintenance agencies to implement this method in order to clear their roads and bridges from debris, dirt, grease, and contaminants. The New York State Department of Transportation employs this cleaning technique in their bridges and roads to either clean the surface, or to prepare the surface for the application of sealants or coatings.

3.5.2.2 Eradication Methods

The most common method of killing microbial life is by the application of biocides - (bio: life form; cide: killer). Biocides are a versatile solution because it comes in many forms such as liquid, powder, gas. Generally, gas or vapor biocides are used to decontaminate materials that have already been colonized by microorganisms. Liquid and powder forms are often used to prevent their growth (e.g. quaternary ammonium compounds are constantly used in pools to prevent the growth of algae). Biocides are the most effective chemicals to eliminate and prevent microbial growth because of their broad variety, intensity, and spectrum (Bott 2011). However, these chemicals can be dangerous for humans and animals, which necessitate precautions in selecting the biocide by considering spectrum of the biocide, toxicity of the biocide, and effects on construction materials.

There are many different kinds of biocides used for cleaning. Some of the most common biocides used for cleaning materials are composed by the following chemicals: oxidizing agents, aldehydes, alcohols, phenolics, organic acids, quaternary ammonium/phosphonium compounds, and Isothiazolinones. The use of the biocide and its characteristics varies depending on which chemical compound they contain. For instance, one of the most common oxidizing agents is chlorine. This compound has been used for many years in both the domestic and industrial world, mainly because of its low cost. Other oxidizing agents are ozone, hydrogen peroxide, and other halogens. Different biocides have different modes of action in order to eradicate microbial activity (Allsopp 2004).

Physical Methods are also employed to eradicate microbial life. These types of methods are also used in order to eradicate microbial life. In the housing industry, it is a common and recommendable practice to control humidity in places where mold growth is developing in order to restrict its growth. As discussed in previous sections, biofilms start to develop when high humidity and temperatures ranging from 25 to 30°C are available (Bastidas-Arteaga et al. 2008). However, it is virtually impossible to control these parameters outdoors.

To eliminate biofilms in industrial equipment it is very common to implement variations to pressure and temperature. Usually, these variations are implemented in closed elements and equipments such as pipelines and boilers where they are easy to control (Bott 2011; Allsopp 2004). UV rays, microwaves and gamma rays have also been employed in order to restrict microorganisms' growth. Gamma radiation has also been successfully implemented to eliminate fungal growth from books after flooding events (Allsopp 2004). Even though, physical methods have been successfully applied in certain industries and fields, it is unlikely that these methods would be successful in highway infrastructure, because it is virtually impossible to control variables such as temperature, humidity, and pressure for long periods of time in outdoors.

3.5.2.3 Preventive Methods.

New technologies on prevention of microorganisms' growth are currently being explored. The use of Titanium Dioxide (TiO_2) and zeolite compounds as additives in the concrete mix have been shown to reduce the growth and development of biofilms in concrete elements (Kurth 2008; Haile and Nakhla 2010).

Titanium dioxide can be used to construct surfaces that are capable of self-cleaning when irritated with UV from sunlight and washed by rainwater. TiO_2's self-cleaning ability is a result of a combination of the photo induced super-hydrophilic and photocatalytic properties of the material (Fujishima and Zhang 2006). Super-hydrophilicity is defined as the ability of the material to have a water contact angle of approximately 0^o while photocatalysis is defined as the ability of the material to decompose pollutants when irritated by UV light. In this process, bacteria and organic build is decomposed by photocatalysis while dust and organic contaminants are washed away by rain by the photo induced super-hydrophilicity as shown in Figure 32. Both processes take place simultaneously on the TiO_2 surface. The following section explains the mechanism behind both processes.

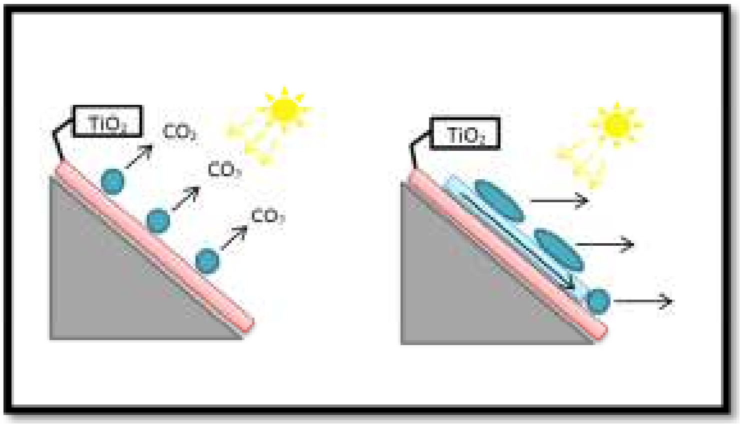

Figure 32
Super-hydrophilic process of TiO2 (Fujishima, A., & Zhang 2006)

- Photo induced super-hydrophilicity. The anatase form of TiO_2 is considered to be a super-hydrophilic (hydro: water; philic: attraction) component when exposed to UV light. When irradiated by UV light, very low contact angles (approximately 0^o) between water and supporting solid is obtained. This causes the water droplets to behave as a layer or a sheet, instead of individual circular droplets. Since TiO_2 is a semiconductor with a bandgap of about 3.0 eV, it produces electrons and holes when exposed to UV light (Fujishima and Honda 1972). The electrons released reduce Ti^{4+} cations to a Ti^{3+} state and the holes oxidize O^{2-} anions releasing oxygen atoms and creating vacancies in the titanium dioxide lattice structure. When the surface is washed, water molecules occupy these vacancies producing adsorbed OH groups and making the surface hydrophilic.
- Heterogeneous Photocatalysis. Heterogeneous photocatalysis accelerates the natural decomposition process of harmful air pollutants and organic compounds. Photocatalytic reaction starts with the formation of electron-hole pairs initiated by energy that is greater than the band gap energy as previously described in photo induced super-hydrophilicity. Once irradiated with UV light, titanium dioxide forms highly oxidizing holes and photo-

generated electrons resulting in hydroxyl radicals and superoxides, respectively (Fujishima, A., & Zhang 2006). The hydroxyl radicals are strong oxidants that rapidly decompose organic and inorganic compounds. Thus, rather than just absorbing pollutants, common of traditional air purification methods, pollutants are decomposed to nonhazardous waste products with little energy requirements (Fujishima, A., & Zhang 2006). A number of studies have been carried out in order to test the self-cleaning and photocatalytic properties of TiO_2 in construction materials. Details of these studies have been presented elsewhere (Hassan 2013).

3.6 Survey Results

Twenty responses were received from a total of 50 questionnaires sent to the state agencies in the US, Figure 33. The response rate received accounted for a total of 40%; it is noted that two responses were received from Washington State representing the marine and coast climatic regions in the state. As expected, many states elected not to participate in the survey because the issue of biofilm growth was not critical for them given the prevailing climatic conditions in these states (low humidity levels, very cold or hot temperatures).

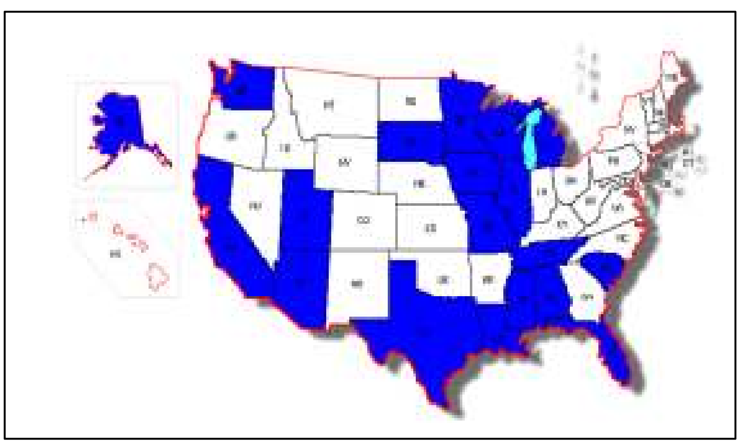

Figure 33
States Responding to the Survey

Figure 34 shows the total number of bridges maintained by each agency in the reporting states as well as the approximate overall bridge conditions for all bridges in the reporting states, on a scale from 1 to 10. The scale rating for bridge condition ranged from one to ten, ten being perfect or like new conditions and 1 being very poor conditions. On average, reporting agencies perceive that the maintained bridges have an overall score of 7 out of 10.

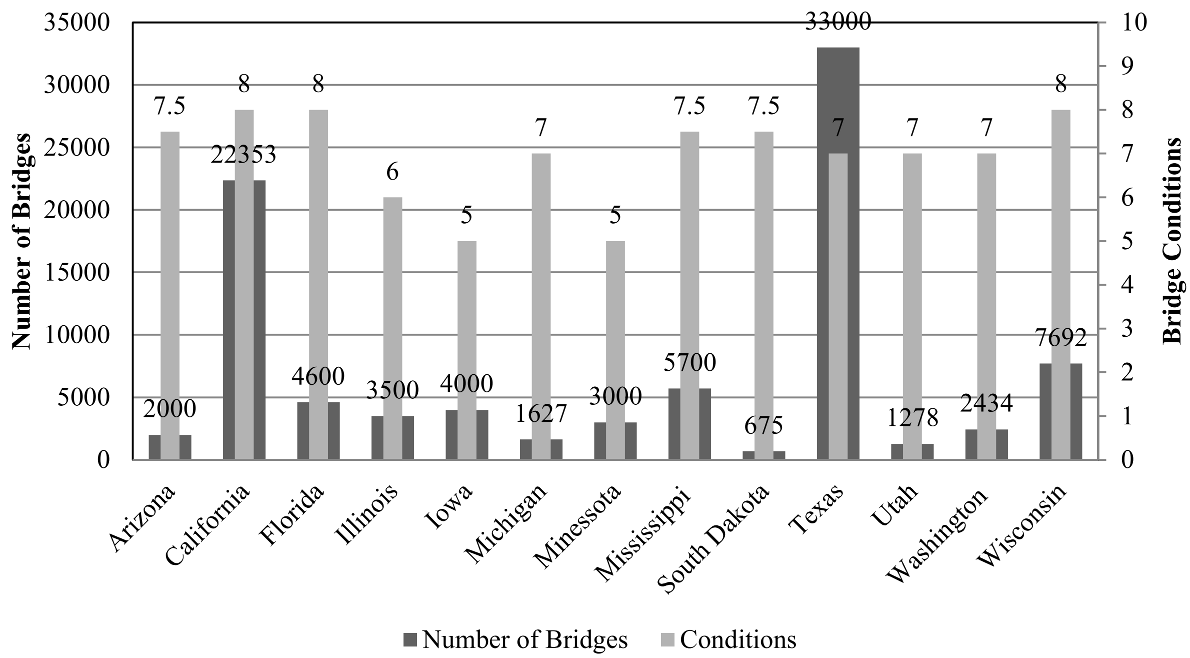

Figure 34
Number of Bridges and Conditions by State

The results obtained from the survey suggest that ten of the states that responded to the questionnaire have experienced some kind of visible biofilm (mold, mildew, fungal, or bacterial) growth on concrete structures. Although biofilm growth develops on concrete surfaces, some states do not take any actions in order to control or solve this issue. The survey inquired about the reason why biofilm growth was not being treated. Responses are shown in Figure 35, where 22% of the responses stated that there was no growth, this can be in most cases attributed to the climatic conditions of the state (low humidity levels, very cold or hot temperatures). 29% of the responses expressed that there was a lack of monetary resources to deal with this issue. Another 21% reported that biofilm growth was not considered a significant issue; therefore, it was not being treated. Many of the states that reported not having mold or mildew growth explained that while they did have mold or mildew growth, they did not consider it a major problem, since the visible stains were minimal. In case these states treated the issue, they only did it in places where it was visible and had high traffic concentrations. Climatic conditions play a very important role in biofilm development. Literature review has shown that biofilm development is only possible when relatively high levels of humidity and temperature are present. Figure 36 presents the percentages of responding states corresponding to each of the climatic regions of the US defined by the DOE.

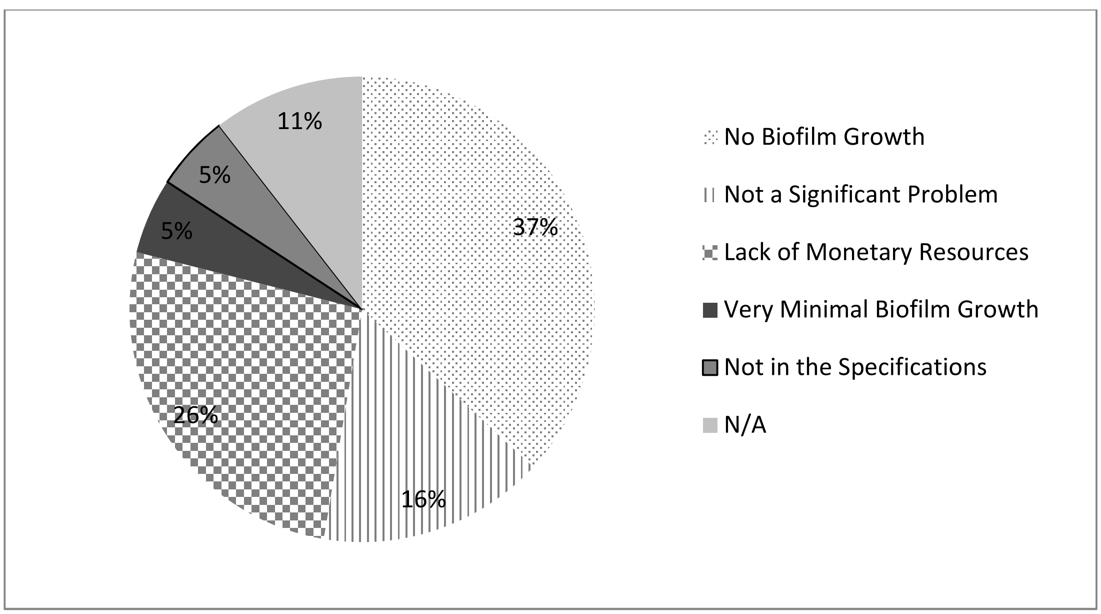

Figure 35
Reasons Why Biofilms Were not Considered a Concern

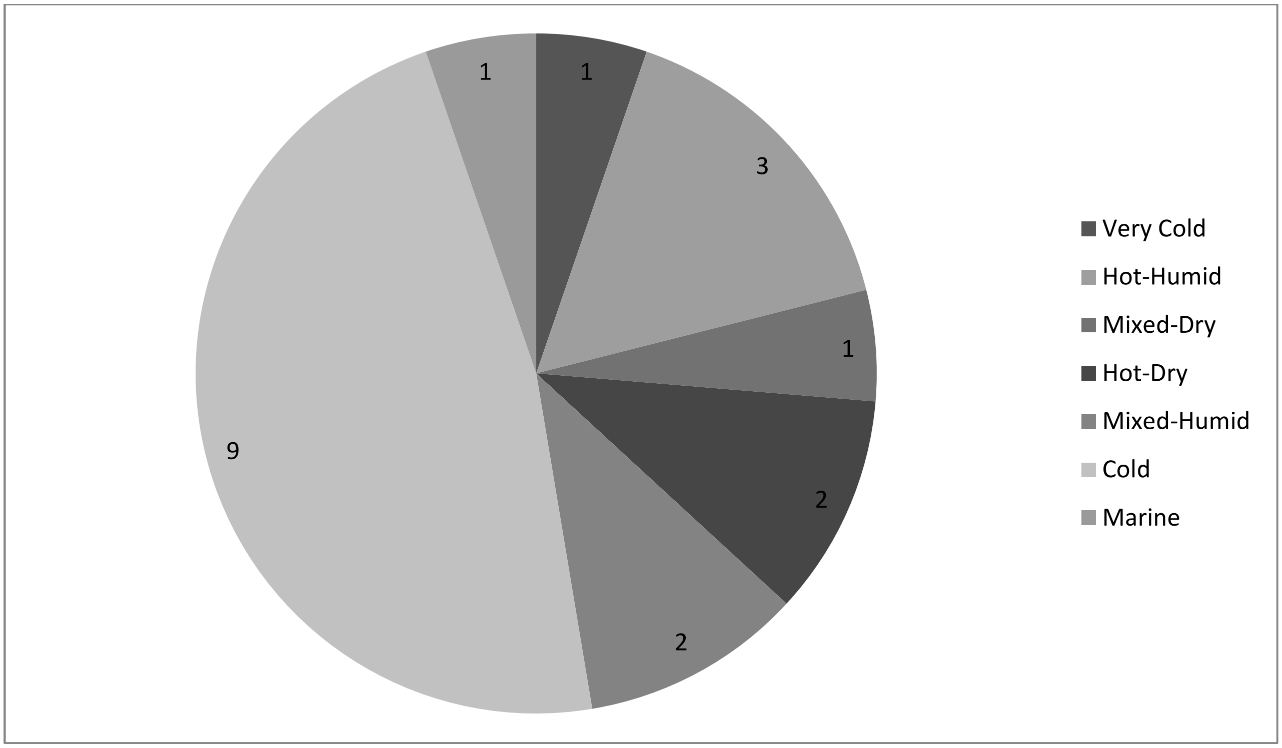

Figure 36
Distribution of Climatic Regions

All the states corresponding to the Hot-Humid climatic region reported biofilm issues as expected. Figure 37 shows how many states reported biofilm growth in each climatic region. As expected, the states that are located in regions with high temperatures and humidity are the ones that are reporting visible biofilm growth on concrete structures.

It is important to mention that none of the participating states responded to the question: "What methods are currently being employed to address biofilm issues?", the reason is because none of the states that participated are currently employing any treatment method to address biofilm issues.

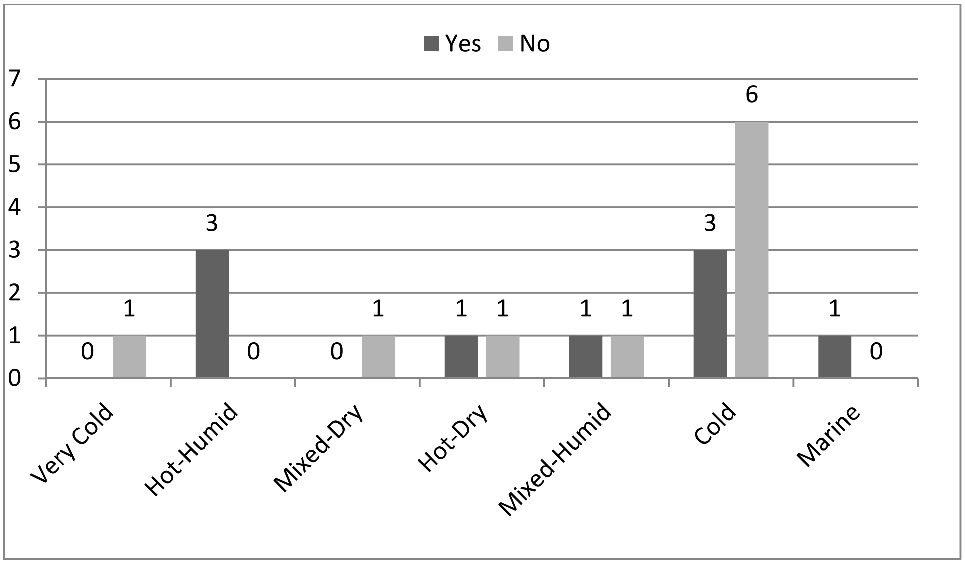

Figure 37
Positive Mold Growth by Climatic Region

3.7 Cost Analysis

To identify the most appropriate methods to eliminate biofilm growth on concrete bridge elements, it is important not only to consider the effectiveness of the method but also its cost. Because of environmental issues, biocides were excluded from this analysis. Although biocides can be employed to eliminate biofilms, strict environmental regulations make its use on concrete bridge elements over water streams very difficult. According to the RSMeans Open Shop Building Construction Data, the costs of pressure washing, sand blasting, dry-ice blasting, and titanium dioxide coatings were estimated (RSMeans Company 2013). Table 8 summarizes the results of the cost analysis and compares four treatment methods over a period of five years. The total cost over five years was calculated by multiplying the application interval by five years. According to this comparison, it seems that on a cost basis, TiO_2 coating is the most cost-effective method since it is only applied once during a period of five years, while the other methods are applied once or twice each year. Furthermore, according to the literature review, mechanical cleaning methods such as pressure washing and sand blasting must be applied once or twice a year to prevent colonization from microorganisms while TiO_2 coatings are estimated to last up to 5 years of service.

Table 8
Cost Analysis Comparisons for Four Common Treatment Methods

Method	Square Foot Price ($/sq. ft.)	Application Interval	Total Cost Over 5 Years ($/sq. ft.)
Pressure Washing	1.88	Once or twice a year	9.8 - 19.6
Sand Blasting	5.58	Once or twice a year	29.6 – 59.2
Dry-Ice Blasting	2.00	Once or twice a year	10.4 – 20.8
Titanium Dioxide Coatings	0.75	Once every 5 years	0.75

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CHAPTER 4 - SUMMARY AND CONCLUSION

The primary objective of this study was to conduct a comprehensive literature review to determine causes of concrete biodeterioration and to present current practices employed or evaluated for cleaning and maintaining vertical concrete elements on bridges. The goal of this review was to identify possible preventive maintenance or construction materials that will enhance the resistance of these structures to biofilm growth and in turn reduce labor, costs, and traveling time delays. Emphasis was given to the methods used in states with climatic conditions similar to the ones encountered in Louisiana (i.e., hot-humid climatic conditions). The literature review showed that the following methods are currently being used to fight biofilm growth on concrete surfaces:

- Pressure washing
- Sandblasting
- CO_2 blasting
- Soda blasting
- Application of biocides
- Temperature, pressure, and humidity control
- UV rays, Gamma rays, and microwaves
- Use of titanium dioxide in the concrete mixture and application of TiO_2 coating
- Zeolite coating.

4.1 Comparative Analysis of Methods

Based on the results of the study, the following table (Table 9), presents a comparative analysis between the different treatment methods. As shown in this table, current methods for cleaning and eradication of biofilm development on highways and bridges such as pressure washing, sand blasting, dry-ice (CO_2) blasting, and soda blasting, require frequent applications.

In addition, these methods have shown poor results since biofilms continue to develop on the structures over time. Further, continuously treating highways and concrete bridges would be economically unsustainable given the large extent of the work to be performed, and the equipment and labor hours needed to accomplish these tasks. This indicates that more practical alternatives to preventative maintenance cleaning methods are needed. Preventive methods such as TiO_2 and zeolites appear the most promising; however, further validation of these innovative techniques is needed prior to implementation.

Table 10 contains a breakdown of each of the methods (sand blasting, soda blasting, dry-ice blasting, pressure washing, biocides, physical methods, TiO_2 Coatings, and zeolite compounds, into four categories:

- Environmental concerns
- Labor safety concerns
- Scheduling interval
- Cost

Each of the methods was awarded points on a scale from 1 to 10 on each of the categories in the table, being ten the worst possible score and one the best. Therefore, the lowest total score represents the best ranked method.

Table 9
Comparative Analysis of Different Treatment Methods for Biofilm

Category	Method	Type	Environmental Concenrs	Scheduling Interval	Abrasive	Cost	Comments
Cleaning	Sand Blasting	Mechanical	Yes	Once or twice per year	Yes	high	Labor Intensive
	Soda Blasting	Mechanical	Yes	Once or twice per year	Yes	high	Labor Intensive
	Dry Ice Blasting	Mechanical	No	Once or twice per year	Yes	Medium	Labor Intensive
	Pressure Washing	Mechanical	Yes	Once or twice per year	Yes	Medium	Labor Intensive
Eradication	Biocides	Chemical	Yes	Depends upon the type	No	high	Does not affect the material properties
	Physical Methods (control temp. and humidity)	Physical	No	Continuous	No	High	Impossible to control outdoors
Preventive	TiO_2 Coatings	Chemical	Yes	Once every 5-10 years	No	Medium	Self-cleans under rain preventing biofilm growth
	Zeolite compounds	Chemical	Yes	Further Investigation Required	No	Medium	Resists bacterial induced deterioration

Table 10
Breakdown of the treatment methods and respective scores

			1	2	3	4	
Category	Method	Type	**Environmental Concenrs**	**Labor Safety Concerns**	**Scheduling Interval**	**Cost**	**Total**
Cleaning	Sand Blasting	Mechanical	8	9	9	8	34
	Soda Blasting	Mechanical	8	7	9	8	32
	Dry Ice Blasting	Mechanical	5	7	9	7	28
	Pressure Washing	Mechanical	7	5	9	7	28
Eradication	Biocides	Chemical	10	10	8	8	36
	Physical Methods (control temp. and humidity)	Physical	3	5	10	10	28
Preventive	TiO_2 Coatings	Chemical	5	6	1	4	16
	Zeolite compounds	Chemical	5	8	10	4	27

4.2 Environmental Concerns

In this section, all the environmental concerns of each of the solution types will be discussed

4.2.1 Cleaning or Abrasive Methods

All the abrasive methods scored relatively high scores in this category, mainly because all of them leave a lot of residue and debris that have become in contact with contaminants and have to be carefully handled and disposed.

Dry-ice is the less environmentally concerning since the dry-ice evaporates as it impacts the surface leaving less residue and debris.

4.2.2 Eradication Methods

Biocides represent a very strong hazard to the environment since they are toxic substances that can be very powerful depending on the type and concentration of the biocide.

The physical methods have relatively low impact on the environment compared to the other methods.

4.2.3 Preventive Methods

These methods have an intermediate impact on the environment and depend mostly in the application method (as a coating or as an additive in the concrete mix).

4.3 Labor Safety Concerns

In this section, all the labor safety concerns of each of the solution types will be discussed

4.3.1 Cleaning or Abrasive Methods

These methods with the exception of biocides, represent the biggest hazard to health. Blasting mediums such as silica and sodium bicarbonate generate diseases in human beings, that's why operators of any abrasive mediums are required to wear safety equipment

4.3.2 Eradication Methods

Biocides are the most dangerous for health among all the methods. These substances are designed to eliminate or eradicate life, and if they're not handled properly, they could represent a mayor treat to human beings.

The physical methods such as pressure, temperature, and humidity control, do not represent a serious threat to humans, however, microwaves and gamma rays generate radiation that can affect health if the proper safety equipment is not utilized.

4.3.3 Preventive Methods

Depending on the application mechanism of the preventive methods, the level of labor safety concern varies. But generally, these concerns are intermediate.

4.4 Scheduling Interval

In this section, all the scheduling interval concerns of each of the solution types will be discussed

4.4.1 Cleaning or Abrasive Methods

Abrasive methods have to be applied every once or twice a year, which is a lot when compared to TiO_2 Coatings. These methods consist in removing or detaching the contaminants from the surface. However, the contaminants and microorganisms that are deeper into the concrete matrix are not removed and continue to reproduce, therefore a new biofilm community re-develops in a relatively short period of time

4.4.2 Eradication Methods

Biocides vary a lot in the scheduling or application intervals. But generally, since these chemical substances are affected and diluted by rain and the environmental conditions, they have to be re-applied in short intervals

Physical methods have to be continuously applied in order for them to be effective, that is why they have the lowest score in this category.

4.4.3 Preventive Methods

The biggest advantage of the preventive methods is probably their durability. TiO_2 Coatings are warranted to last up to five years, but phone interviews with experts showed that the self cleaning properties of the material can last up to 10 years.

4.5 Cost

In this section, all the cost concerns of each of the solution types will be discussed

4.5.1 Cleaning or Abrasive Methods

Cleaning and abrasive methods can be expensive when taking in consideration the scheduling intervals and disposal concerns. Overall, these methods require high amounts of blasting media and personnel in order to be applied, which is why their prices can be expensive.

4.5.2 Eradication Methods

Mainly because of their scheduling intervals, both biocides and physical methods can be very expensive to apply in the highway industry

4.5.3 Preventive Methods

From the three types of methods, TiO_2 Coatings and zeolite compounds seem to be the less expensive ones thanks to the long application intervals.

From the results of the literature review, it appears that pressure washing, TiO_2 and zeolite coatings are the most applicable methods to the transportation industry. For its long lasting effect, TiO_2 coatings seem to have an advantage over pressure washing, since the TiO_2 coatings last up to 10 years of service, while pressure washing needs to be conducted on a periodical basis (approximately once or twice a year). Furthermore, water usage and disposal over water streams is becoming a more difficult task since more and stricter environmental regulations are emerging.

Results of the synthesis also showed that concrete mix design parameters, especially porosity and water/cement ratio, play an important role in controlling biofilms. As surface roughness of concrete increases, void ratio also increases creating more space for water retention, which can support microorganism growth. In addition, water/cement ratio has been proved to influence the bioreceptivity of concrete to certain deteriorating species of microorganisms. As the water proportion in a concrete mix increases, the permeability of concrete also increases; thus resulting in larger areas for moisture and nutrient retention.

Based on the results of this synthesis, a comparative analysis was conducted to identify strengths and weaknesses of each treatment method. Based on this analysis, it is recommended that a follow-up study be conducted in order to identify biofilm mechanisms in Louisiana and to conduct an experimental program to test a number of cleaning and preventive methods in the laboratory. Four research tasks were developed for the follow-up study. Based on the results of the follow-up study, a recommended state of practice should be developed to address biofilm growth in Louisiana. The developed practice should present recommend application of preventive methods as well as modifications to current concrete design and production practices in order to minimize or delay biofilm growth.

4.6 Recommendations for Future Research

Based on the results of this study, it is recommended that the following investigation should be carried:

- What are the main microorganisms involved in biodeterioration on concrete surfaces in Louisiana?
- What is the durability of TiO_2 coatings on concrete exposed to the environmental conditions of the state of Louisiana?
- Field investigation testing the real efficiency of the different methods to prevent biofouling mentioned in this study
- What is the best concentration of TiO_2 in the coatings for biofilm development prevention
- Develop a field study employing zeolite compounds to prevent biofilm development and verify its efficiency and economic viability.

APPENDIX A - SURVEY

Questionnaire for LADOTD Research Project on Evaluating Best Practices for Cleaning and Maintaining Concrete Bridge Railings from Biofilm Growth

The Louisiana Department of Transportation and Development is currently evaluating best practices employed or evaluated for cleaning and maintaining concrete bridge railings and vertical structures from biofilm growth (mold, mildew and fungus) across the nation. Biofilms growing on concrete bridge railings and vertical surfaces create stains on concrete, which not only have negative impacts on its aesthetic value but also its durability. Many DOT's clean and use coatings to prevent biofilms from forming. The goal of this review is to identify possible preventive maintenance practices or construction materials that will enhance the resistance of these structures to mildew growth and in turn reduce labor, costs, and traveling time delays. Based on this review, the research team will identify and summarize current cleaning methods, predicted cleaning schedules, and preventive measures to rehabilitate and preserve these structures.

We would like to ask for your assistance in providing us with information about your state experience with various cleaning and maintaining methods used to prevent growth of biofilms (mold, fungus and mildew) on concrete structures. Please return the completed questionnaire to Marwa Hassan, Assistant Professor, Louisiana State University, through email to marwa@lsu.edu or by mail to 3128 Patrick f Taylor hall, Baton Rouge, LA 70803. This information will be used to help develop better control strategies of biofilm (mold, fungus and mildew growth) on concrete bridges in Louisiana. Your input is greatly appreciated. Should you have any questions regarding this questionnaire, please call Marwa Hassan at (225) 578-9189. The results of this survey will be shared with the respondents.

Please return the questionnaire by December 1, 2012. We appreciate your timely response.

Thanks

Section 1: Background Data

1) *What is the number of concrete bridges maintained by your agency?*

2) *On a scale of 1-10, (10 represents a bridge with new or like-new conditions, and 5 and above as good conditions), rate the condition of Concrete bridges in your agency?*

Section 2: Significance

3) *Is concrete mildew growth or staining on vertical surfaces of the bridge a concern for your agency?*

☐ ***Yes***

☐ ***No***

4) *If yes, is there a preventative maintenance program to address this issue?*

Yes ☐

No ☐

5) *If No, Why is it not a concern?*

☐ ***Lack of Monetary resources***

☐ ***Other: please explain why?:***

6) *If No, and the reason is lack of funding, would you address the issue if funding becomes available?*

Yes ☐

No ☐

7) Is concrete bridge railings cleaning and maintenance part of your state annual bridge maintenance program?

Yes ☐

No ☐

Section 3: Performance

8) Of the following cleaning/treatment methods, which biofilm (mold, fungus and mildew) prevention methodology is used or has been evaluated in your state for concrete bridge railings and vertical surfaces in the past ten years and what were their general performances?

Cleaning/ Treatment Method	Is the procedure scheduled/or done on need basis?	If scheduled, provide frequency of application	Relative performance of method against concrete stains			
			1 - 3 yrs.	3 to 6 yrs.	No improvement	Negative contribution
Cleaning (i.e., rotating brushes, etc.)						
Pressure Washing						
Paints						
Other Preventative coatings						
Sealants						
Combination of treatments						

Comments

If a combination of treatments is used, please describe it here:

If performance depends on other factors, please mention them here:

If cost depends on other factors, please mention them here:

Section 4: New construction/Special Purpose additives

9) Are you adding additives to the concrete mix to reduce the growth rate/eliminate biofilms?

☐ ***Yes***

☐ ***No***

10) If yes, please name the additive,

11) Are you adding special finishes to the concrete mix to reduce the growth rate/eliminate biofilms?

☐ ***Yes***

☐ ***No***

12) If yes, please name the finishing material

Section 5: Additional Information

13) ***Other than the treatment methods identified in this survey, does your state have experiences with other biofilm (mold, fungus and mildew) control treatment or cleaning methods?***

☐ Yes

☐ No

Comments

Section 6: Contact information

Please provide your contact information so we can follow up with you:

State:

DOT District:

Contact Person name:

Email:

Phone:

Fax:

APPENDIX B - TIO_2 WARRANTY

pureti
Sustainable Solutions ... for a Cleaner World

<u>LIMITED PRODUCT WARRANTY</u>

PURETi warrants to DISTRIBUTOR that, for the limited warranty period described below, the surfaces treated with any Product (defined as PURETi Base, Clear, Clean or Coat), if applied in compliance with the applicable Documentation, will demonstrate sustained photocatalytic properties. PURETi further warrants that, with handling and maintenance consistent with the Documentation, the Product will not peel, crack, or discolor under normal conditions for a period of three (3) years from the date of application to interior surfaces and five (5) years from the date of application to exterior surfaces.

For any valid claim presented under this Warranty, PURETi will (i) provide enough additional Product to replace the non-conforming Product, or (ii) at the option of PURETi, refund the original cost of the Product, excluding the labor costs for coating application. Under no circumstances will PURETi's obligations under this Limited Warranty exceed the purchase price of the original Product.

Exclusions. This Limited Warranty does not cover, and PURETi will have no liability for, any damage or failure of the PURETi photocatalytic solution caused by or due to any of the following:

1. Lightning, earthquake, windstorm, hurricane, tornado, hail, fire, flood, or other major natural events of acts of God.
2. Cracks, breaks, voids, or degradation in the substrate to which the coating has been applied.
3. Discoloration, changes in visual appearance, or surface dirt accumulation due to graffiti, bird droppings, paint splatter or other similar macro sosling.
4. Misuse or neglect.
5. Failure of the underlying surface for any reason.
6. The FAILURE, DEFECT, OR DAMAGE RESULTING FROM OR CONNECTED WITH, FAILURE OR DAMAGE TO THE WALL OR FOUNDATION FOR THE BUILDING
7. STRUCTURAL DEFECTS OR FAILURE OF SUBSTRATE DUE TO IMPROPER DESIGN OR MAINTENANCE.
8. Application of any non-approved substance on top of the PURETi treated surface or the use of any non-approved cleaning method such as high pressure power washing or highly acidic cleaners.

Warranty Claims. For a claim to be considered valid by PURETi, DISTRIBUTOR must notify PURETi within thirty (30) days of the discovery of the alleged defect in the PURETi Product covered by this Limited Warranty.

Warranties Disclaimed. THIS LIMITED WARRANTY IS IN PLACE OF ALLOTHER WARRANTIES, EXPRESS OR IMPLIED. PURETi EXPRESSLY DISCLAIMS ANY OTHER WARRANTIES, INCLUDING WARRANTIES OF MERCHANTABILITY AND FITNES FOR A PARTICUAR PURPOSE.

April 18, 2013

PURETi Group, LLC / 261 Fifth Avenue – 12th Fl / NY, NY 10016
T: 855.5PURETI / E: elen@pureti.com / www.pureti.com

APPENDIX C - COST ANALYSIS

All prices were calculated according to RSMeans Open Shop Building Construction Cost Data 2013.

Pressure Washing

Crew:

A-1H = 449.60$/Day

449.60$/Day ÷ 8 Labor Hrs/Day = 56.2 $/Hr

56.2 $/Hr * 0.03 Hr/Sq.ft = 1.69$/Sq.ft

Crew Total: 1.69$/Sq.ft

Equipment

Pressure Washer: 51.50 $/Day

51.50 $/Day ÷ 8 Labor Hrs/Day = 6.44 $/Hr

6.44 $/Hr * 0.03 Hr/Sq.ft = 0.19 $/Sq.ft

Equipment Total: 0.19 $/Sq.ft

Pressure Washing Total = Equipment + Crew

1.69$/Sq.ft + 0 .19 $/Sq.ft

= 1.88 $/Sq.ft

Sand Blasting

Crew: 465.60$/Day

465.60$/Day ÷8 Labor Hrs/Day = 58.2 $/Hr

58.2 $/Hr * 0.085 Hr/Sq.ft = 4.95 $/Sq.ft

Crew Total: 4.95 $/Sq.ft

Equipment:

Sand Blaster: 59.5 $/Day

59.5 $/Day ÷ 8 Labor Hrs/Day = 7.44 $/Hr

7.44 $/Hr * 0.085 Hr/Sq.ft = 0.63 $/Sq.ft

Equipment Total: 0.63 $/Sq.ft

Sand Blasting Total = Equipment + Crew

4.95 $/Sq.ft + 0.63$/Sq.ft

= 5.58 $/Sq.ft

Projection over time

Year	2008	2009	2010	2011	2012	Avg
Avg Inflation Rate (%)	3.8	-0.4	1.6	3.2	2.1	**2.06**

Pressure Washing Over 5 Years

2013 (Actual)	**2014**	**2015**	**2016**	**2017**	**Total**
1.88 $/Sq.ft	1.92 $/Sq.ft	1.96 $/Sq.ft	2.0 $/Sq.ft	2.04 $/Sq.ft	**9.8 $/Sq.ft**

Sand Blasting Over 5 Years

2013 (Actual)	**2014**	**2015**	**2016**	**2017**	**Total**
5.58 $/Sq.ft	5.7 $/Sq.ft	5.81 $/Sq.ft	5.93 $/Sq.ft	6.1 $/Sq.ft	**29.12**

Dry-Ice Blasting Over 5 Years

2013 (Actual)	**2014**	**2015**	**2016**	**2017**	**Total**
2.00 $/Sq.ft	2.04 $/Sq.ft	2.08 $/Sq.ft	2.12 $/Sq.ft	2.16 $/Sq.ft	**10.4 $/Sq.ft**

APPENDIX D – IRB APROVAL

Application for Exemption from Institutional Oversight

Unless qualified as meeting the specific criteria for exemption from Institutional Review Board (IRB) oversight, ALL LSU research/ projects using living humans as subjects, or samples, or data obtained from humans, directly or indirectly, with or without their consent, must be approved or exempted in advance by the LSU IRB. This Form helps the PI determine if a project may be exempted, and is used to request an exemption.

LSU
Institutional Review Board
Dr. Robert Mathews, Chair
131 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
F: 225.578.6792
irb@lsu.edu
lsu.edu/irb

– Applicant,Please fill out the application in its entirety and include the completed application as well as parts A-E, listed below, when submitting to the IRB. Once the application is completed, please submit two copies of the completed application to the IRB Office or to a member of the Human Subjects Screening Committee. Members of this committee can be found at http://www.lsu.edu/screeningmembers.shtml

– A Complete Application Includes All of the Following:
- **(A)** Two copies of this completed form and two copies of part B thru E.
- **(B)** A brief project description (adequate to evaluate risks to subjects and to explain your responses to Parts 1&2)
- **(C)** Copies of all instruments to be used.
  - *If this proposal is part of a grant proposal, include a copy of the proposal and all recruitment material.
- **(D)** The consent form that you will use in the study (see part 3 for more information.)
- **(E)** Certificate of Completion of Human Subjects Protection Training for all personnel involved in the project, including students who are involved with testing or handling data, unless already on file with the IRB. Training link: (http://phrp.nihtaining.com/users/login.php.)
- **(F)** IRB Security of Data Agreement: (http://www.lsu.edu/irb/IRB%20Security%20of%20Data.pdf)

1) Principal Investigator: Marwa Hassan **Rank:** Assistant Professor

Dept: CMIE **Ph:** 2255789189 **E-mail:** marwa@lsu.edu

2) Co Investigator(s): please include department, rank, phone and e-mail for each

none

IRB# E5953 LSU Proposal # ______
Complete Application
Human Subjects Training

3) Project Title: Investigation of Best Practices for Maintenance of concrete Bridge Railings

Study Exempted By:
Dr. Robert C. Mathews, Chairman
Institutional Review Board
Louisiana State University
203 B-1 David Boyd Hall
225-578-8692 | www.lsu.edu/irb
Exemption Expires: 10/16/2015

4) Proposal? (yes or no) yes **If Yes, LSU Proposal Number** 39075-1

Also, if YES, either
- (●) **This application completely matches the scope of work in the grant**

OR
- ( ) **More IRB Applications will be filed later**

5) Subject pool (e.g. Psychology students) Department of transportation state agencies

*Circle any **"vulnerable populations" to be used:** (children <18; the mentally impaired, pregnant women, the ages, other). Projects with incarcerated persons cannot be exempted.

6) PI Signature Marwa Hassan **Date** 03/30/2012 (no per signatures)

**** I certify my responses are accurate and complete.** If the project scope or design is later changes, I will resubmit for review. I will obtain written approval from the Authorized Representative of all non-LSU institutions in which the study is conducted. I also understand that it is my responsibility to maintain copies of all consent forms at LSU for three years after completion of the study. If I leave LSU before that time the consent forms should be preserved in the Departmental Office.

Screening Committee Action: Exempted ✓ Not Exempted ____ Category/Paragraph 2

Reviewer Mathews **Signature** Robert C Mathews **Date** 10/17/12

THE VITA

Angel Lence was born in 1987 in Maturin, Venezuela. In 2010, he finished his Bachelor of Science in Civil Engineering from Universidad Metropolitana in Caracas, Venezuela. Angel worked two years for Helen,C.A. as a scheduling and operations engineer . He joined Louisiana State University in January 2012 to pursue a Master of Science in Engineering Science degree.